

Analysis of Human Stepping Time Intervals Using Acceleration Sensors

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Abstract: - Gait analysis plays an important role in characterizing individuals and each condition and gait analysis systems have been developed using various devices or instruments. However, most systems do not catch synchronous stepping actions between right foot and left foot. For obtaining a precise gait pattern, a synchronous walking sensing system is developed, in which a pair of acceleration and angular velocity sensors are attached to left and right shoes of a walking person and their data are transmitted to a PC through a wireless channel. Walking data from 19 persons of the age of 14 to 20 are acquired for walking analysis. Stepping time diagrams are extracted from the acquired data of right and left foot actions of stepping-off and-on the ground, and the time interval analyses distinguish between an ordinary person and a person injured on left leg, and a stepping recovery process of the injured person is shown. Synchronous sensing of stepping action between right foot and left foot contributes to obtain precise stepping patterns.

Key-Words: - gait, analysis, acquisition system, acceleration sensor, pattern extraction, daigram

1 Introduction

Gait pattern of person characterizes individual and each condition. The precise gait pattern may be one of the measures for recognizing individuals [1]-[4]. Gait analysis systems using acceleration sensor have been developed for medical rehabilitation [5], identification of portable device user [6], etc. However, most systems do not catch synchronous stepping actions between right foot and left foot. In this paper, a synchronous walking sensing system is developed, where a pair of acceleration and angular velocity sensors are attached to left and right shoes of a walking person and their data are transmitted to a PC through a wireless channel. Walking data from 19 students of the age of 14 to 20 are acquired for walking analysis. From acquired data, stepping time diagrams are extracted and the difference of stepping time intervals between an ordinary person and a person injured on left leg and the recovery process of the injured person are shown.

2 Human walking

Human is an only creature who moves by erect bipedal gait or walking. Always birds as ostrich and penguin and temporarily animals as dog, bear, monkey and ape move by bipedal walking, but they cannot move in an erect posture. Human walking is characterized by locomotion manners and speed. Usually human walking features the action in which

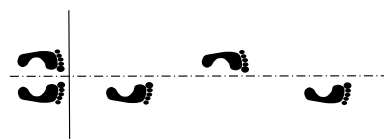


Fig. 1. Feet touch positions of walking movement.

pivot foot alternately changes and either foot touches on the ground. Fig.1 shows an example of surface touchdown positions of left and right feet when a person stands and starts walking from the right step and moves forward.

The walking action is regarded as a rotation movement around the touched ground or floor [7]. In this case, the rotation energy does not exceed the gravity energy, as follows:

$$mv^2 / r \leq mg \quad (1)$$

where v , r and m are the walking velocity, the gravity centre and the mass of a person, and the acceleration of the gravity is $g = 9.80[m/s^2]$. Then the maximum value of walking velocity is obtained as

$$v_{\max} = \sqrt{rg}. \quad (2)$$

For the height $r = l[m]$ of the gravity centre of a person, the walking velocity is limited to $v_{\max} = 3.13[m/s]$.

If the moving velocity of a person exceeds v_{\max} , the moving action becomes running. In the case of

the normal walking, the horizontal momentum is delivered to the next action at a full efficiency, and the vertical momentum disappears by collision between the foot and the ground, while the gravity energy of the gravity centre is preserved by Achilles' tendon and delivered to the next action by kicking the ground. In the case of the abnormal walking that the weight is supported by both feet, the velocity vector of the gravity centre is restricted toward one way and the left and right momentum by zigzag movement is vanished in addition to the vertical momentum and so the energy efficiency of this walking is inferior to the normal walking.

Real walking manner accompanies with so complicated actions interlinked by feet, leg, body, moving velocity, etc, that walking patterns can be utilized to identification of individuals and each condition. One of parameters to characterize the walking is the duty factor which is the ratio of foot touchdown interval to a walking period. The duty factor for the normal walking ranges over 0.6 to 0.7 [8]. In this paper, walking actions by stepping-off and -on the ground are detected concentrating on time sequence.

3 Walking data acquisition system

Fig.2 shows a walking data acquisition system using a couple of acceleration and angular velocity sensors. A person taking a pair of shoes attached

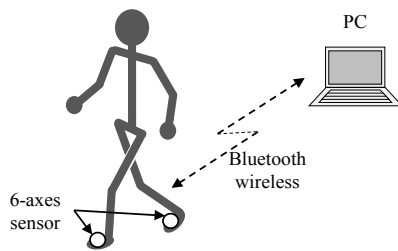


Fig.2. Walking data acquisition system.

Table 1. Specifications of sensor.

Acceleration sensor	InvenSense MPU-6050
Sampling rate	max 1000Hz (1 to 255msec)
Accelerometer Feature	±2G, ±4G, ±8G and ±16G
Gyroscope Feature	±250dps, ±500dps, ±1000dps and ±2000dps
Magnetic Field sensor	Aichi Steel AMI306
Barometer	Freescale MPL3115A2

with sensors moves by walking at a flat ground or floor, while the respective sensor transmits data to a



Fig. 3. Overview of sensor.

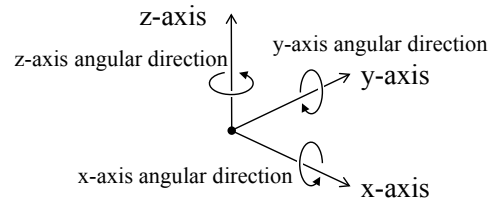


Fig.5. Shoes attached to sensors.

PC through Bluetooth wireless channel. Table 1 shows specifications of the sensor TSND121 which detects 3-axes accelerations and 3-axes angular velocities and additionally earth magnetism and atmospheric pressure. The PC controls sensors by instructions of start and stop and processes the acquired data of 6-axes accelerations and angular velocities. Fig.3 shows an overview of the sensor in comparison with a 500yen coin of 2.65cm diameter, where x, y and z axes in acceleration sensing are drawn on the surface. Fig.4 shows directions of rotation angles around x, y and z axes in angular velocity sensing. Fig.5 shows a picture of shoes attached to the sensors with x axis of acceleration directed forward. The sensors are attached firmly to the shoes at the stable position [9], [10].

4 Data acquisition of walking

At the floor of the college building, walking data were acquired from 19 male and female students of the age of 14 to 20, one of whom had been injured on left leg but could join in the experiments. The walking manner is explained as follows: a subject person stands at the start point and raises both tiptoes in order to synchronize between left and right sensors and then begins to walk from the right

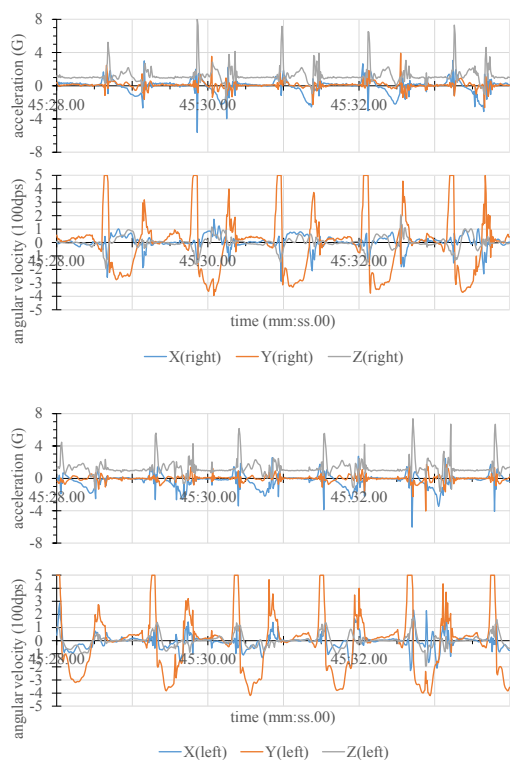


Fig.6. Acceleration and angular velocity responses for an ordinary person.

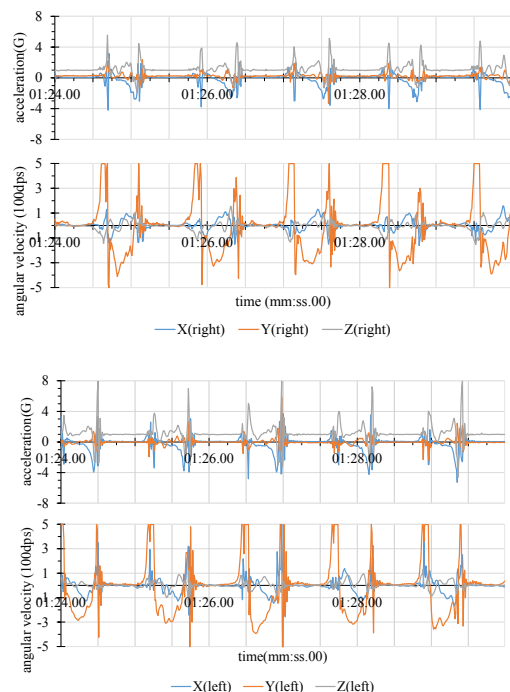


Fig.7. Acceleration and angular velocity responses for an injured person

or left foot. Fig.6 shows partial waveforms of x, y

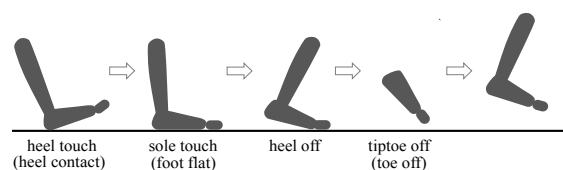


Fig.8. Stepping action of a foot.

and z components of acceleration and angular velocity on right foot and left foot of an ordinary person, and Fig.7 shows those of a person injured on left leg, where each waveform indicates almost steady response after initial irregular response. The responses for the injured person seem to be more irregular than those for the ordinary person. In these responses, the time positions of large amplitude of x and z components of accelerations and y component of angular velocities are regarded as unique changing points of stepping off and on the ground [11]. We consider that the negatives short pulse of x acceleration and the positive short pulse of z acceleration occurs simultaneously with the positive to negative rebound pulse of y angular velocity and so the time when the stepping-on changes to stepping-off is the time on the peaks of x and z acceleration pulses and the zero-crossing of y angular velocity rebound pulse. And we consider that the negative pulses of x and z accelerations occurs simultaneously and so the time when the stepping-off changes to stepping-on is the time on the peaks of x and z acceleration negative pulses. The above stepping-off and -on interpretations are supported by the foot actions of Fig.8. There, first a heel touches on the ground, a sole adheres to the ground, the heel rises with a tiptoe on the ground, and at last the tiptoe rises off the ground with the heel. The first action gives downward x and z accelerations and the last action gives the rebound rotation around y axis. Fig.9 and Fig.10 show x and z components of accelerations and y components of angular velocities for the injured person at the second experiment and the third experiment, respectively, at the interval of two weeks.

5 Analysis of stepping time intervals

In order to evaluate the stepping actions, we extract the time intervals of stepping off and on the ground from the acceleration and angular velocity responses. As mentioned in the above chapter, from the unique changing points in Fig.6 and Fig.7, we obtain the

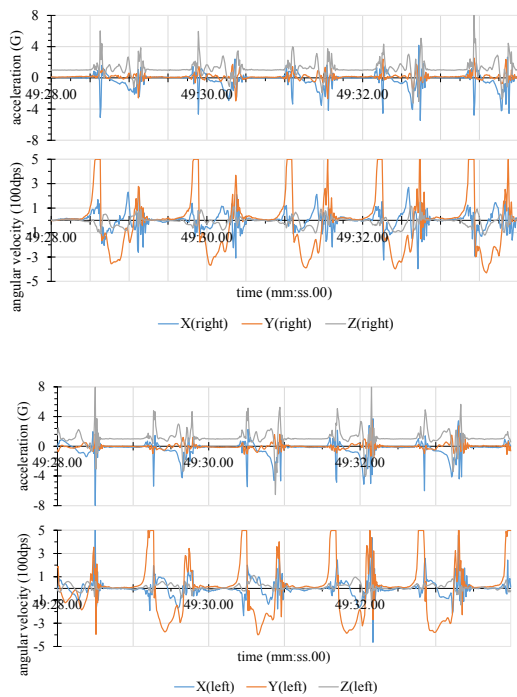


Fig.9. Acceleration angular velocity responses for the injured person at the second experiment.

stepping time diagrams of the right and left feet.

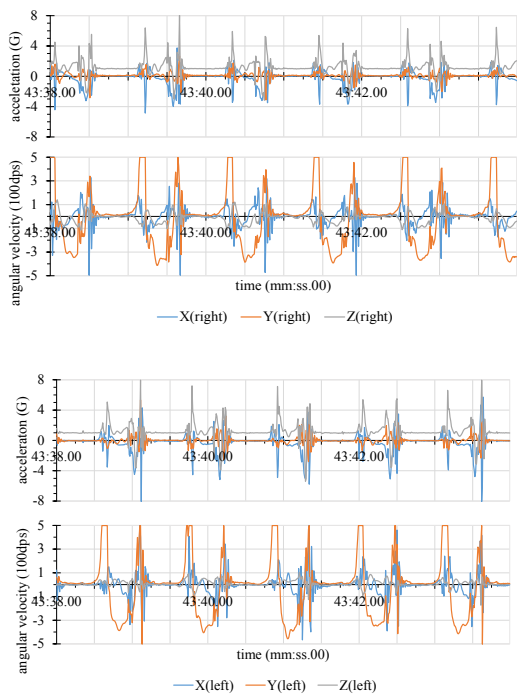


Fig.10. Acceleration and angular velocity responses for the injured person at the third experiment.

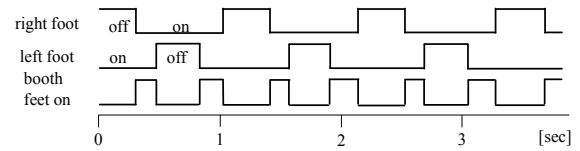


Fig.11 Stepping time diagram for the ordinary person.

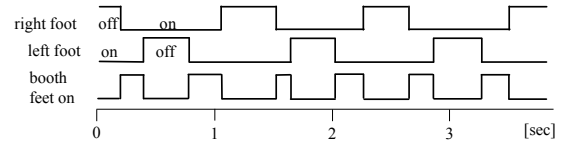


Fig.12. Stepping time diagram for the injured person.

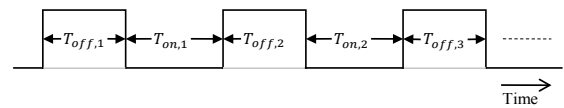


Fig.13. Stepping-off and-on time intervals.

Fig.11 and Fig.12 show the stepping time diagrams of the ordinary person and the injured person, respectively, where another time diagram illustrates the time intervals simultaneously stepping on the ground. The simultaneously stepping-on time diagram of the ordinary person is more balanced than that of the injured person. The simultaneous stepping-on occurs two times in a pair of the right and left steps. The stepping-off and-on time intervals are evaluated by a model of Fig.13, where $T_{off,k}$ is stepping-off time interval and $T_{on,k}$ is stepping-on time interval. The respective N intervals give the average values

$$\bar{T}_{off} = (1/N) \sum_{k=1}^N T_{off,k} \tag{3}$$

$$\bar{T}_{on} = (1/N) \sum_{k=1}^N T_{on,k} \tag{4}$$

and the variances

$$\sigma_{off}^2 = (1/N) \sum_{k=1}^N (T_{off,k} - \bar{T}_{off})^2 \tag{5}$$

$$\sigma_{on}^2 = (1/N) \sum_{k=1}^N (T_{on,k} - \bar{T}_{on})^2 \tag{6}$$

Table 2. Statistics of time intervals of stepping-off and -on.

	Ordinary person			Injured person		
	Right foot	Left foot	Both feet	Right foot	Left foot	Both feet
\bar{T}_{off}	0.395	0.367		0.379	0.378	
σ_{off}	0.015	0.030		0.031	0.017	
\bar{T}_{on}	0.759	0.790		0.828	0.830	
σ_{on}	0.038	0.046		0.034	0.018	
$T_{on-right-left}$			0.182			0.212
$\sigma_{on-right-left}$			0.021			0.028
$T_{on-left-right}$			0.214			0.238
$\sigma_{on-left-right}$			0.036			0.013

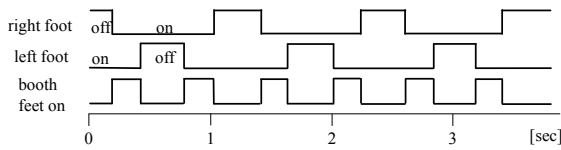


Fig.14. Stepping time diagram of 2nd experiment for the injured person.

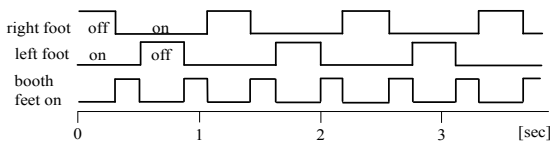


Fig.15. Stepping time diagram of 3rd experiment for the injured person.

From the time intervals in Fig.11 and Fig.12, we obtain the average values and the standard deviations of stepping-off and -on time intervals of the right foot and the left foot for the ordinary person and for the injured person. Similarly, we define the simultaneously stepping-on time intervals and obtain the average values and standard deviation of the simultaneously stepping-on time intervals for the ordinary person and for the injured person. Table 2 shows the average values and the standard deviations of these time intervals in second ($N=11$). We evaluate the above data by duty factors and rate factors. The duty factor is expressed as

$$D = \bar{T}_{on} / (\bar{T}_{on} + \bar{T}_{off}) \quad (7)$$

and the rate factor is defined as

$$R = (\bar{T}_{on-right-left} + \bar{T}_{on-left-right}) / (\bar{T}_{on} + \bar{T}_{off}) \quad (8)$$

$$= (\bar{T}_{on} - \bar{T}_{off}) / (\bar{T}_{on} + \bar{T}_{off})$$

where \bar{T}_{on} , \bar{T}_{off} , $\bar{T}_{on-right-left}$ and $\bar{T}_{on-left-right}$ are the average values during a stride by both feet and the average stride cycle is given by

$$\bar{T}_{stride} = \bar{T}_{on} + \bar{T}_{off} \quad (9)$$

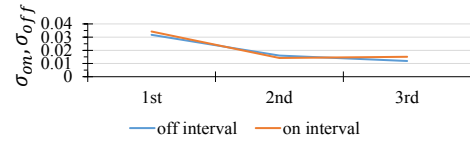


Fig.16. Standard deviations of right foot stepping time interval in second.

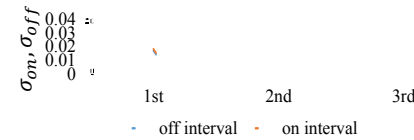


Fig.17. Standard deviations of left foot stepping time interval in second.

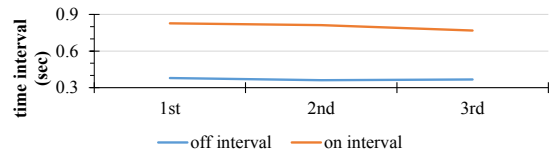


Fig.18. Average values of right foot stepping time interval.

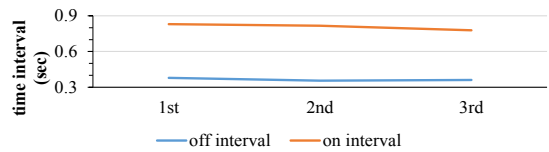


Fig.19. Average values of left foot stepping time interval.

Eq. (7) and Eq. (8) gives $R = 2D - 1$, and $R = 0$ or $D = 1/2$ corresponds to the critical gait from walking to running. From Table 2, $D = 0.671$, $R = 0.343$ and $\bar{T}_{stride} = 1.15[s]$ for the normal person and $D = 0.686$, $R = 0.373$ and $\bar{T}_{stride} = 1.21[s]$ for the injured person are obtained. It is seen that the injured person moved at the 8% lower rate than the ordinary person.

Fig.14 and Fig.15 shows the stepping-off and -on time diagrams derived from Fig.9 and Fig.10. From the time intervals in Fig.12, Fig. 14 and Fig.15 for the injured person, we obtain the average value and the standard deviations of the stepping-off and stepping-on time intervals of the 1st, 2nd and 3rd experiments of the right foot as $\bar{T}_{off,n,right}$, $\bar{T}_{on,n,right}$, $\sigma_{off,n,right}$, $\sigma_{on,n,right}$ and those of the left foot as $\bar{T}_{off,n,left}$, $\bar{T}_{on,n,left}$, $\sigma_{off,n,left}$, $\sigma_{on,n,left}$ ($n=1,2,3, N=11$). Fig.16 and Fig.17 show convergence process of standard

deviations of stepping-off and stepping-on time intervals of the right foot and the left foot, respectively. Fig.16 and Fig.17 show that the stepping action of the injured person recovers and become stable according to time progress. Fig.18 and Fig.19 show convergence process of average values of stepping-off and stepping-on time intervals. From the 3rd values of $\bar{T}_{off,3,right} = 0.367[s]$, $\bar{T}_{on,3,right} = 0.769[s]$ and $\bar{T}_{off,3,left} = 0.360[s]$, $\bar{T}_{on,3,left} = 0.779[s]$, we obtain the average stride cycle for the injured person

$$\begin{aligned}\bar{T}_{stride} &= (\bar{T}_{off,3,right} + \bar{T}_{off,3,left} + \bar{T}_{on,3,right} + \bar{T}_{on,3,left}) / 2 \\ &= 1.14[s]\end{aligned}$$

and the duty factor for the injured person

$$D = \frac{\bar{T}_{on,3,right} + \bar{T}_{on,3,left}}{2\bar{T}_{stride}} = 0.680 .$$

Moreover, we obtain the average values and the standard deviations of the simultaneously stepping-on time intervals at the 1st, 2nd and 3rd stages for the injured person, as $\bar{T}_{on-right-left,1} = 0.212[s]$, $\bar{T}_{on-left-right,1} = 0.238[s]$, $\bar{T}_{on-right-left,2} = 0.234[s]$, $\bar{T}_{on-left-right,2} = 0.234[s]$, $\bar{T}_{on-right-left,3} = 0.222[s]$, $\bar{T}_{on-left-right,3} = 0.190[s]$ and thus the rate factor for the injured person

$$R = (\bar{T}_{on-right-left,3} + \bar{T}_{on-left-right,3}) / \bar{T}_{stride} = 0.362 .$$

From these results, it is seen that the walking parameters and stepping pattern of the injured person approaches those of the ordinary person.

6 Conclusion

A walking data acquisition system using a couple of acceleration and angular velocity sensors attached to each foot is developed. The system is applied to acquisition of walking data from 19 male and female students including a male student in the recovery process of injured left leg. In the sensor data, x and z components of accelerations and y component of angular velocities are used for analysis of walking. The stepping-off and -on time diagrams, the derived duty factors and rate factors characterize the walking of the ordinary student and injured student, and give a recognition of the recovery process of the injured student. Synchronous sensing of stepping action between right foot and left foot contributes to obtain precise stepping patterns. The other data of accelerations and angular velocities may be used for the recognitions of individual and each condition in the future.

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