Sensors & Transducers, Vol. 155, Issue 8, August 2013, pp. 120-127

www.sensorsportal.com

Sensors & Transducers

http://www.sensorsportal.com

Development of Precession Instrumentation System for Differentiate Walking from Running in Race Walking by Using Piezoelectric Sensor

[1] Didik R. SANTOSO, [2] Taufiq A. SETYANTO

[1] Instrumentation Lab. Physics Dept., Brawijaya University, Jl. Veteran Malang, 65145, Indonesia

[2] Indonesian Hydrodynamics Lab.-BPPT, Jl. Hidrodinamika Surabaya, 60112, Indonesia

[1] Tel.: 62-341-575833, fax: 62-341-575834

[1] E-mail: dieks@ub.ac.id

Received: 3 June 2013 /Accepted: 12 August 2013 /Published: 20 August 2013

Abstract: In this paper, a precession instrumentation system for measurement and characterization of human foot stress has been developed. The system is very useful to differentiate walking from running in race walking sport, by identification of the foot loss of contact with the ground. The system was developed in two main units: sensing unit (RTU) and signal processing unit (MTU). The RTU consist of piezoelectric stress sensor module and data acquisition module. The data acquisition is developed based on microcontroller to achieve the system as small as possible, but powerful. The MTU consist of computer system and several program procedures to identify the foot stress signals and to differentiate walking from running. Data communication between RTU and MTU can be conducted through wires by using RS485 protocol, or wirelessly by adding a pair of radio transceiver device. The system can be operated by online and real time. Result of the experiments show that the developed system has good performance. *Copyright © 2013 IFSA.*

Keywords: Race walking, Judging, Instrumentation, Piezoelectric sensor, Signal processing.

1. Introduction

To get better achievements in the race walking competitions, understanding of the rules and certainty in judging is very important. Judging of the race walking is based on the IAAF rule, no.230; which states: "Race Walking is a progression of steps so taken that the walker makes contact with the ground, so that no visible (to the human eye) loss of contact occurs. The advancing leg must be straightened (i.e. not bent at the knee) from the moment of first contact with the ground until the vertical upright position" [1]. Hence, there are only two basic rules: first is the knee cannot be bent from the moment until the vertical upright position of the body, and second is the walker must always have at least one foot on the ground, and this is the feature that differentiates race walking from running [2, 3].

Fig. 1 shows how to differentiate walking from running. This figure is taken from Race Walk Officiating Handbook, USA Track & Field 2008 [4]. It can be seen, that in walking event, the walkers must always have at least one foot on the ground, and in running event, the walkers has "flying" condition.

Furthermore, although the judging of the competition currently is based only on view of the human eye, but it is necessary the existence of an instrument that can be used to for a more rigorous identification. It is very useful not only to give certainty justification in competition, but also can be

Article number 1295

used by athlete during practices in order to avoid unwanted disqualification when competition. To provide the intended instrument, some researchers have proposed several systems [5-7], of course each of them with own merits and limitations.

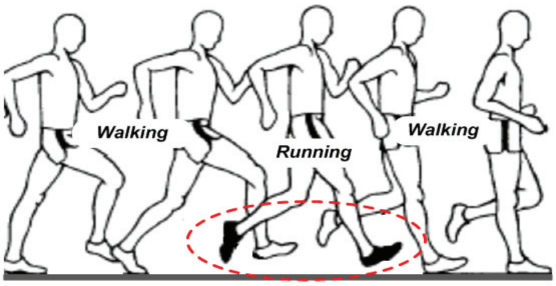

Fig. 1. Differentiates walking from running.

In this paper, a precession instrumentation system for measurement and characterization of human foot stress is proposed. The system has capabilities to differentiates walking from running by identify loss of contact with the ground.

2. Design of the Instrumentation System

Fig. 2 shows a block diagram of the proposed instrumentation system. It is consists of several modules that can be grouped into two units: remote terminal unit (RTU) and master terminal unit (MTU). The RTU is sensing unit; it is built of sensor module and data acquisition module. The MTU is control unit; it is a personal computer device that equipped with signal processing program procedures. Data communication between RTU and MTU can be conducted through wires by using RS-485 protocol, or wirelessly by adding a pair of RF radio transceiver device.

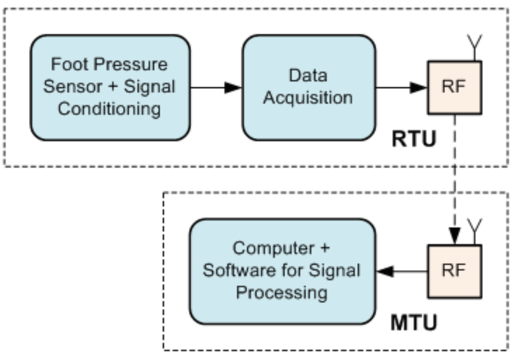

Fig. 2. Block diagram of the instrumentation system.

In the RTU, sensor module senses the presence of foot stress that indicates foot makes contact with the ground. There are four points to be measured, whose function will be explained later. Output signals from each sensor then conditioned by signal conditioning circuits (SC). The data acquisition module converts analog signals from SC into digital form, and then transmits the data to the MTU. In the signal processing module, the data will be identified by certain rules and be decided of whether a person was being walking or running conditions, included the time of events.

2.1. Sensor Module

The sensor module is feet pressure sensors, which deals with foot stress signal sensing and conditioning. To sense existence of the foot stress, we put four sensor elements at four selected points. The first sensor is placed in the front section of right foot (call as RF), the second sensor at the back section of right foot (RB), the third sensor at the front section of left foot (LF), and the fourth sensors in the back section of left foot (LB), as shown in Fig. 3.

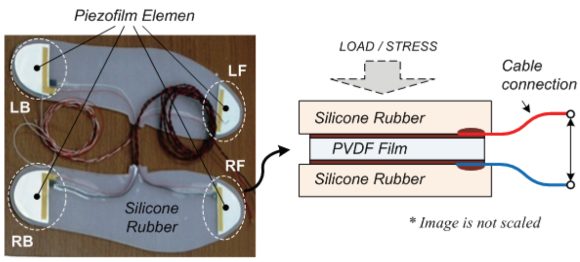

Fig. 3. Sensor elements, positions and mechanism.

Sensing element is made of PVDF film, which is a kind of piezoelectric material. In the both sides of PVDF film connected to metal cable to make electric connection. The film clamped by silicone rubber in both sides to make elastic when stepped on. In here, PVDF film will generate electric charge on both surfaces when loaded or subjected by mechanical stress [8]. If the stress occurs in the thickness or *z*-direction only, then the equation for the voltage mode can be expressed by:

$$V = g_{33}\sigma_3 t \tag{1}$$

V : open loop voltage (V);
σ_3 : mechanical stress for z-axis (N/m^2);
g_{33} : piezofilm stress constant in z-axis (V.m/N);
t : PVDF film thickness (m);

The piezoelectric sensor can be modeled as a voltage source (V_p) coupled in series with a capacitor (C_p) [9]. And by the principles of parallel plate capacitor, value of C_p has a linear relationship with the area of piezoelectric elements. Therefore, for the same stress, the sensor with a larger area will generate a larger voltage.

Furthermore, piezoelectric sensors require high input impedance signal conditioning circuit in order to suppress loading effects caused by measuring device. In this case, we use a charge amplifier circuit as shown in Fig. 4. In addition, because the charge amplifier is operated on inverting mode, so it need an inverting amplifier circuit to return the signal to its normal phase, as well as for signal amplifications.

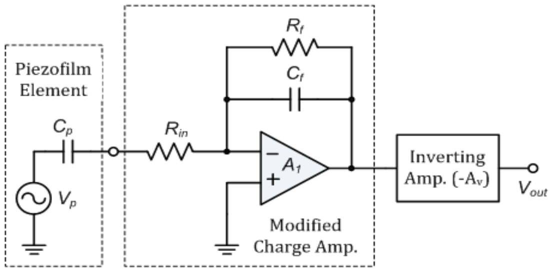

Fig. 4. Signal conditioning circuit.

The output voltage (V_{out}) of the circuit in Fig. 4 can be expressed as:

$$V_{out} = A_v \frac{Z_{(R_f, C_f)}}{Z_{(C_p, R_{in})}} V_p \tag{2}$$

Completion Eqs. 2 is given in [10]:

$$V_{out} = A_v \frac{C_p}{C_f} V_p \text{ ; for } (\omega_1 << \omega << \omega_2), \tag{3}$$

where

$$\omega_1 = \frac{1}{C_f R_f} \text{ and } \omega_2 = \frac{1}{C_p R_{in}} \tag{4}$$

Eqs. 3 can be interpreted that the output voltage of the sensor depends on the area of the piezoelectric element (equivalent C_p) and magnitude of the foot stress (equivalent V_p).

2.2. Data Acquisition Module

The data acquisition (DAQ) module was designed with the following assignments:

- To sampling the analog signals (RF, RB, LF, and LB) from sensor module with a certain sampling time;
- To convert the analog signals into digital data;
- To send the digital data to the MTU via RS485 network (wire) or radio transceiver (wireless).

The main component of DAQ module is a microcontroller PIC16F876. It has some features inside such as 5-channels ADC with 10 bits resolution, TIMER, USART, 8K × 14 words of flash program memory, 368 × 8 bytes of RAM [11]. Fig. 5 shows the DAQ module that used in this project.

It should be explained here that the internal ADC of microcontroller only capable recognize positive signals (typically in the range of 0 to 5 Volts). Hence, before converted by the internal ADC, the analog signal from the SC should be increased to a certain dc level. This is accomplished by dc-offset circuit. We use 2.5 volts for offset, with the intention that the signal has same swings in up and down.

In view of the microcontroller based DAQ system, firmware is required to manage hardware system driving, signals capturing, and data transmitting (to MTU). The firmware is developed by the use of MPLAB assembly codes.

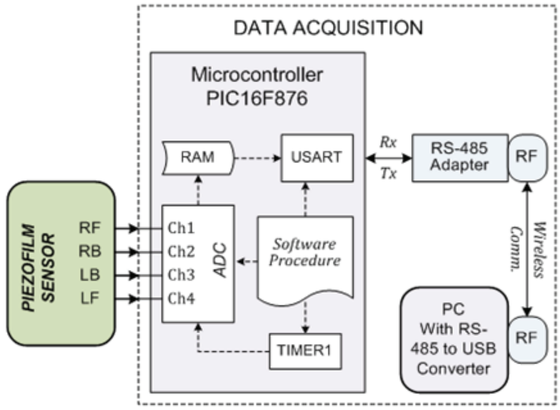

Fig. 5. Data acquisition module.

3. Signal Characterization

In order to understanding the differences between walking and running, firstly we take the voltage signals from foot sensors by using multi channels digital oscilloscope. For this purpose, the sensor module is inserted into the shoes, and then used for walking and running activities. Signals are recorded in the four data points that have been determined (RF, RB, LF, and LB).

Results of experiments are given in Fig. 6 and Fig. 7 for walking and running activities respectively. In those figures, when the sensor pressed by the foot (at the ground), it will generate electric voltages, and when the foot release the stress, the voltage will down rapidly. In here, one cycle is a complete one-step event, such as for RB-RF-LB-LF, and back to RB.

To simplify the captured signals that do not look complicated, we add the signals of each foot; so henceforth we have two signals only, e.g. the right foot (R) and the left foot (L) signals, as shown in Fig. 8 for walking and Fig. 9 for running. According to these figures, we have four important events:

(1). RB hit the ground (RBU)
(2). RF release the ground (RFD)
(3). LB hit the ground (LBU)
(4). LF release the ground (LFD)

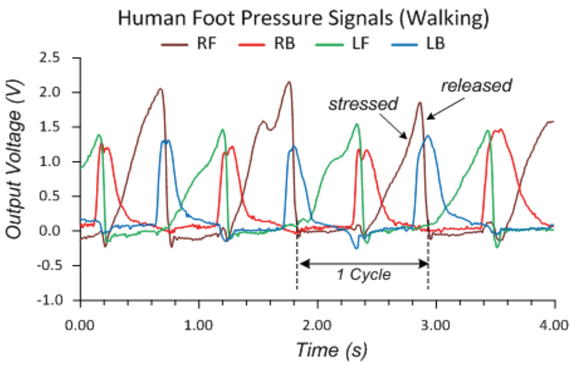

Fig. 6. Human walking signals.

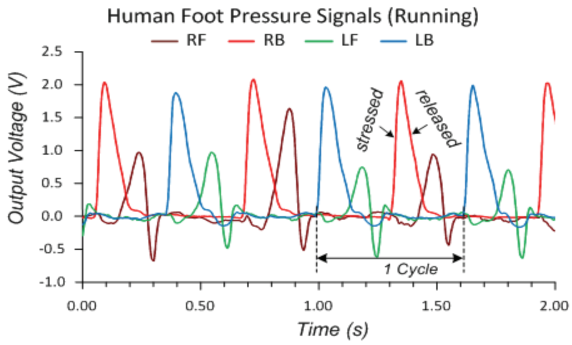

Fig. 7. Human running signals.

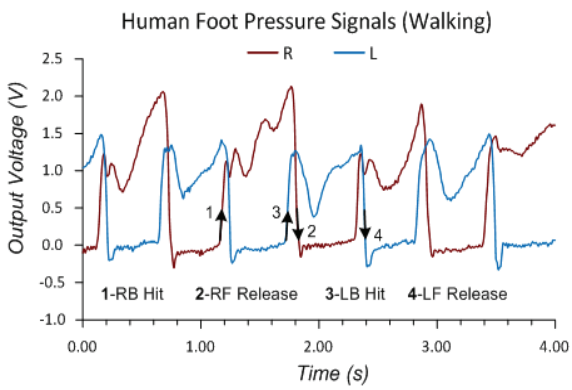

Fig. 8. R-L signals when walking.

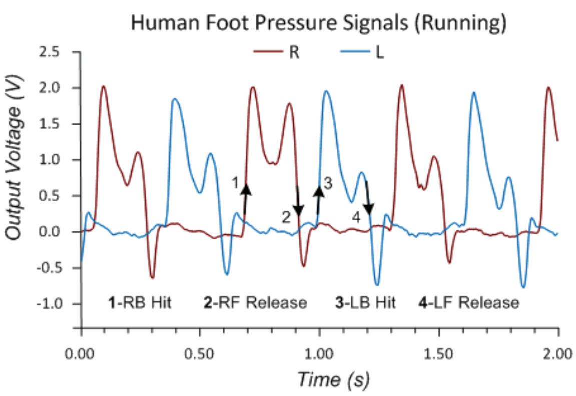

Fig. 9. R-L signals when running.

Here, we can differentiate walking and running activities clearly. We can see that time series of the walking activity in one-cycle is (1-3-2-4) or (RBU – LBU – RFD – LFD), and time series of the running activity in one-cycle is (1-2-3-4) or (RBU – RFD – LBU – LFD). Time within interval (1-2) is the right foot makes contact with the ground, and time within interval (3-4) is the left foot makes contact with the ground. Transition step from right foot to left foot is given by (2) to (3) and transition step from left foot to light foot is given by (4) to (1).

Moreover, transition from right foot to left foot and vice versa is an important thing to make differences between walking and running activities. In walking events, transition from the right foot to the left foot, and conversely, has overlapping time ((3) precedes (2) or (1) precedes (4)). It means, in walking event, at least one foot is always has contact with the ground. But, in running events, transition from the right foot to the left foot, and conversely, has no overlapping contact time. Then, we can say that the running event has "flying" condition.

4. Signal Processing

Based on the information that has been presented above, the following description will be given several procedures for signal processing.

4.1. Threshold Voltage

Threshold voltage (V_T) is needed in order to make the signal only has two values. It is very important to be used for time identification of the events of RBU, RFD, LBU, and LFD.

Rules of the program procedure is if voltage of the signal sampling is higher than V_T, then value of the signal sampling becomes "high" (5 Volts), if lower than V_T, then it is become "low" (0 Volt). Fig. 10 may useful to help clarify this statement. In here XY is the original signal, and XYN is new corresponding signal after threshold procedure applied.

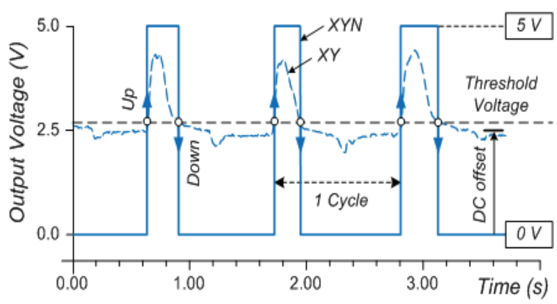

Fig. 10. Rule of the threshold voltage.

Hence by the rule, four original signals (RF, RB, LF, and LB) and **n** number of sampling, the program procedure is given below:

for n:= 1 to max do
if RF[n] > V_T then RFN[n]:=5; else RFN[n]:=0;
if RB[n] > V_T then RBN[n]:=5; else RBN[n]:=0;
if LF[n] > V_T then RFN[n]:=5; else LFN[n]:=0;
if LB[n] > V_T then RFN[n]:=5; else LBN[n]:=0;

4.2. Determination of Rise & Fall Time

As discussed earlier, to identify and make differences between walking and running activities, we can use foot transitions while the stepped. Transition from right foot to left foot is given by RFD (2) to LBU (3), and transition from left foot to right foot is given by LFD (4) to RBU (1). Please see again Fig. 8 and Fig. 9.

Time identification is made by detection of two pairs of the signals: RFD-LBU and LFD-RBU, what is come first. Then, the time when RFD and LFD going down, as well as RBU and LBU going up, are must be determined. So we have four important time events as shown in Fig. 11 and Fig. 12, there are:

- TRU, time for RBN going up
- TRD, time for RFN going down
- TLU, time for LBN going up
- TLD, time for LFN going down

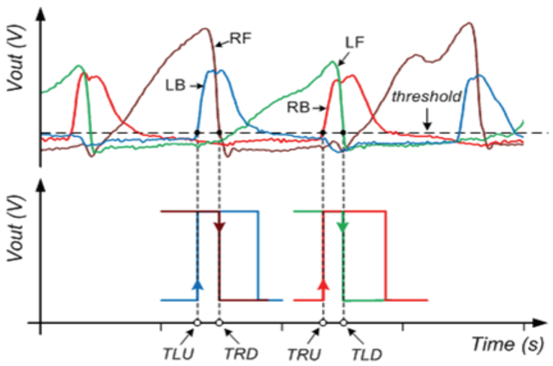

Fig. 11. Time series of walking.

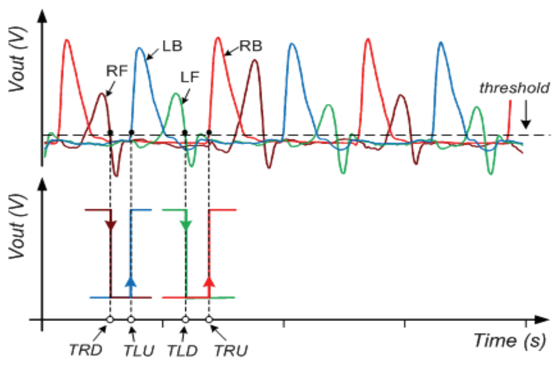

Fig. 12. Time series for running.

Rise time ("going up") is pointed by changes in the voltage value of the signal from 0 Volt become 5 Volts, and the fall time ("going down") is changes the voltage from 5 volts become 0 volt. Then, the procedure to detect the rise time and the fall time is given as below:

{Transition from Right to Left}
RBU:=0; LFD:=0; //how many transitions?
for n:=1 to max do
if (RBN[n-1]=0) and (RBN[n]=5) then
RBU:=RBU+1; TRU[RBU]:=Time[n];
if (LFN[n-1]=5) and (LFN[n]=0) then
LFD:=LFD+1; TLD[LFD]:=Time[n];

{Transition from Left to Right}
LBU:=0; RFD:=0; // how many transitions?
for n:=1 to max do
if (LBN[n-1]=0) and (LBN[n]=5) then
LBU:=LBU+1; TLU[LBU]:=Time[n];
if (RFN[n-1]=5) and (RFN[n]=0) then
RFD:=RFD+1; TRD[RFD]:=Time[n];

4.3. Decision of Running from Walking

Decision of running from walking is made by using time determination that has been described in Fig. 11 (walking) and Fig. 12 (running). Based on those figures, time series in the walking activity is TLU-TRD-TRU-TLD- and so on, whereas time series in the running activity is TRD-TLU-TLD-TRU- and so on.

However, the signal must be paired; wherein TLU must be paired with the TRD, and the TRU must be paired with TLD. So the "pulse" that does not have a pair should be discarded. Fig. 13 shows the unpaired signal both in walking and running events.
Rearrange time of the signals for discard unpaired pulse is given below:

if (RBU<LFD) then N1:= RBU else N1:= LFD
if (LBU<RFD) then N2:= LBU else N2:= RFD

for i:=1 to N1 do
if (ABS(TRU[i]-TLD[i])) > (ABS(TRU[i+1]-TLD[i]))
then TRU[i]:=TRU[i+1];
if (ABS(TLD[i]-TRU[i])) > (ABS(TLD[i+1]-TRU[i]))
then TLD[i]:=TLD[i+1];
for i:=1 to N2 do
if (ABS(TLU[i]-TRD[i])) > (ABS(TLU[i+1]-TRD[i]))
then TLU[i]:=TLU[i+1];
if (ABS(TRD[i]-TLU[i])) > (ABS(TRD[i+1]-TLU[i]))
then TRD[i]:=TRD[i+1];

Finally, the procedure to identify the existence of running events is:

for n:= 1 to N1 do
if (TRU[n]>TLD[n]) then Alert:="RUNNING"
for n:= 1 to N2 do
if (TLU[n]>TRD[n]) then Alert:="RUNNING"

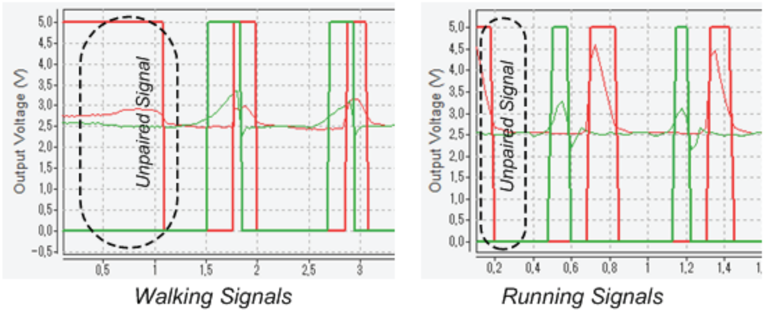

Fig. 13. Unpaired pulse in walking and running events.

4. Implementation of the System

Implementation diagram of the instrumentation system to identify of walking or running events by online and real time is given in Fig. 14. The sensor system is used to detect the foot stresses and convert to the voltages within range of 0 to 5 volts, depend on stress quantity. Data acquisition (DAQ) converts analog signals from sensor to the 10 bits digital data, then transmitted to the MTU by wire or wirelessly by using radio transceiver (RF). On the MTU, data is received by computer system via RF transceiver, and then processed by using developed signal processing software. The program procedures as described above are used to identify running from walking events.

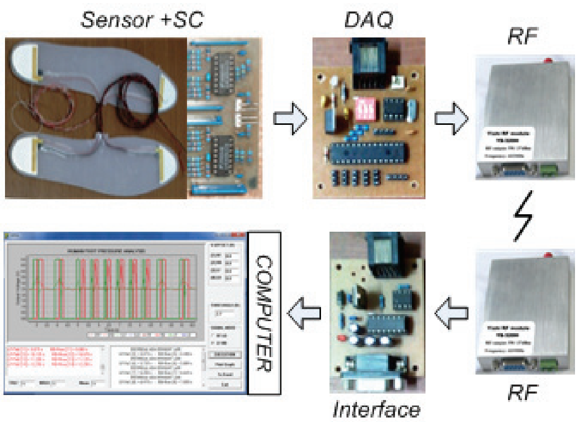

Fig. 14. Implementation of the system.

In the developed system above, DAQ has five-channel analog inputs, which are used to capture the output signals from the sensor module. The uses of the five channels are as follows:

- Ch-1 for Right Foot - Front Section (RF)
- Ch-2 for Right Foot - Back Section (RB)
- Ch-3 for Left Foot - Front Section (LF)
- Ch-4 for Left Foot - Back Section (LB)
- Ch-5 for Reference (REF)

Ch-5 (REF) is used to check the value of the dc-offset voltage, to ensure that the Ch-1 up to Ch-4 has given the appropriate voltage offset.

Implementation of instrumentation system to measure and record of the walking and running activities, is carried out by inserting the piezoelectric sensor into the shoes, and topped with a pedestal to keep the sensor in safe condition. Then, the shoe is used for walking or running. Result of experiments is given in Fig. 15. In this figure, brown color signal is RF, red color is RB, green color is LF, and blue color is LB. By providing dc-offset of 2.5 Volts, then the signal will fluctuate on that value.

By provide threshold voltage at 2.7 Volts, signals in Fig. 15 then process become two level signals (pulses) as shown in Fig. 16. However, in here only two signals that displayed, while to displays the other two signals, can be done by clicking on the options provided by the program. By looking at the figure, we can immediately differentiate between walking and running. In walking signals, appears the overlapping "pulses" at the time of the shift legs. But in running signals, the overlapping pulses is does not appears, and it has delay time between LF and RB (see black circles).

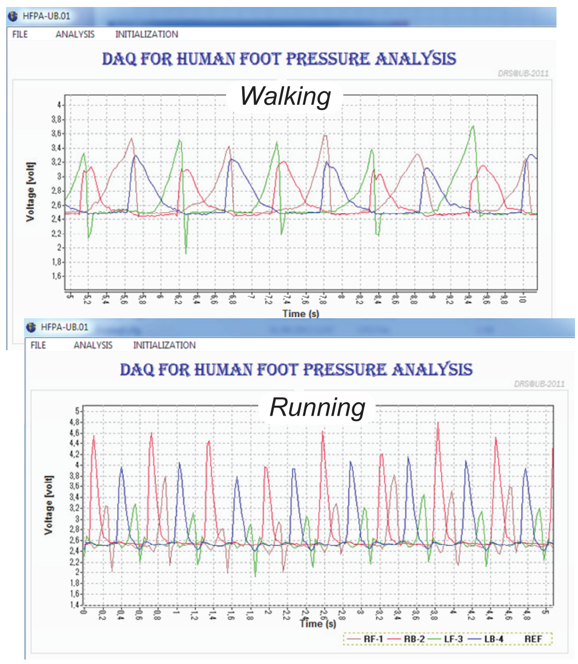

Fig. 15. Signal capturing by developed system.

Fig. 16. Signal identification being walking or running.

Fig. 17 shows when both activities are recorded. First part of the recorded signals is walking events, middle part is running events, and last part is walking events again. The time when running event occurs is given in black circle. Here, it appears clearly that the developed system has ability to detect the presence of running events, including when it happened.

Moreover, some researchers also explained that the identification of running and walking activities can be carried out by using the frequency response, in which the frequency of the walking is in the range of (0.5 - 1.5) Hz, while the running is in the range of (1.0 - 3.0) Hz [12]. In here, by using the developed signal processing software procedure, it can be given clearly as shown in Fig. 18.

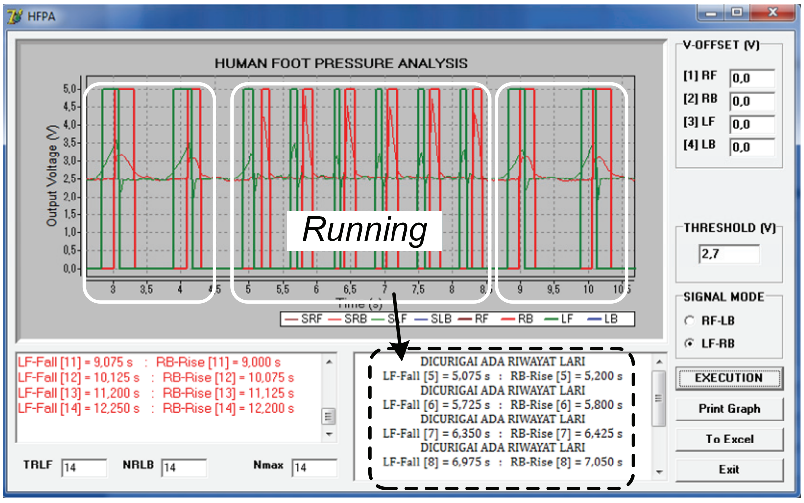

Fig. 17. Signal identification being walking or running.

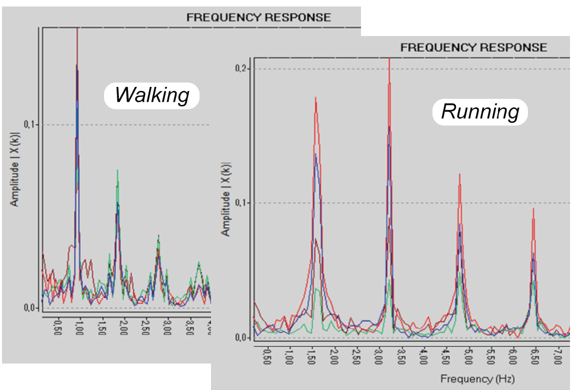

Fig. 18. Frequency response of walking and running.

In addition, the developed instrumentation system may also be used in medical fields, particularly for gait analysis and learn about biomechanics of the foot. Some publications of the research in this field can be found in [13-16].

5. Conclusions

To improve performance in race walking sport, the use of instrumented judging system becomes important. It is very useful not only for athletes, but also for coaches and judges to avoid unnecessary disqualification. In this project, a precession instrumentation system to identify walking or running activities has been developed. The principle of the instrumentation system is to measure foot stress at four places simultaneously, and by the use of measuring signals then detects the existence of loss of foot contact with the ground.

The system was developed in two main units: sensing unit (RTU) and signal processing unit (MTU). The RTU consist of piezoelectric stress sensor module and data acquisition module. The data acquisition is developed based on microcontroller to achieve the system as small as possible, but powerful. The MTU consist of computer system and several program procedures to identify the foot stress signals and to differentiate walking from running. Data communication between RTU and MTU can be conducted through wires by using RS-485 protocol or wirelessly by using radio telemetric system. The system can be operated by online and real time.

References

[1]. IAAF Competition Rules 2012-2013 (http://www.iaaf.org).

[2]. G. A. Westerfield, The Use of Biomechanics in the Judging of Race Walking, in *International Race Walk Forum,* Shenzhen, China, 23 March, 2007.

[3]. V. Racic, A. Pavic, J. M. W. Brownjohn, Experimental identification and analytical modeling of human walking forces: Literature review, *Journal of Sound and Vibration,* No. 326, 2009, pp. 1–49.

[4]. Race Walk Officiating Handbook, *Track & Field,* USA, 2008 (www.usatf.org).

[5]. A. Amigo, Electronic System for Loss of Contact Control in Race Walking (http://www.vrwc.org.au).

[6]. C. Avila, E. Dickinson, B. Moore, K. Rayworth, Dynamic Device for Real Time Acquisition of Angular Flexion of the Knee Joint During Race Walking, *Worcester Polytechnic Institute*, 2012. Available in (http://www.wpi.edu/Pubs).

[7]. A. A. Razak, A. Zayegh, R. K. Begg, Y. Wahab, Foot Plantar Pressure Measurement System: A Review, *Sensors*, Vol. 12, 2012, pp. 9884-9912.

[8]. Gautschi, Piezoelectric Sensoric, *Springer- Germany*, 2002.

[9]. Ehag, Piezofilm sensor technical manual, *Measurement Specialist, Inc*., USA, 1999.

[10]. D. R. Santoso, Abdurrouf, L. Nrriyah, Development of a Simple Traffic Sensor and System with Vehicle Classification Based on PVDF Film Element, *Sensors & Transducers,* Vol. 126, Issue 3, March 2011, pp. 74-84.

[11]. PIC16F876 datasheet (http://www.microchips.com).

[12]. B. T. Humphreys, K. O. Genc, G. P. Perusek, P. R. Cavanagh, Algorithm for Identification of Running, Walking, and Standing Activity in Force Data (http://www.asbweb.org/conferences/2007/195.pdf).

[13]. H. M. Schepers, Ambulatory Assessment of Ankle and Foot Dynamics, *IEEE Transactions on Biomedical Engineering*, Vol. 54, No. 5, May 2007, pp. 895-902.

[14]. J. Perttunen, Foot Loading in Normal and Pathological Walking: Academic dissertation, *University of Jyväskylä*, 2002.

[15]. E. B. Lohman, K. S. B. Sackiriyas, R. W. Swen, A comparison of the spatiotemporal parameters, kinematics, and biomechanics between shod, unshod, and minimally supported running as compared to walking, *Physical Therapy in Sport*, Vol. 12, 2011, pp. 151-163.

[16]. J. Yun, User Identification Using Gait Patterns on UbiFloorII, *Sensors*, Vol. 11, 2011, pp. 2611-2639.