Medical Equipment Insights

SHORT REPORT

Pedometer for Running Activity Using Accelerometer Sensors on the Wrist

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Abstract: The Nokia Wrist–Attached Sensor Platform (NWSP) was developed at the Nokia Research Center during the NUADU project to facilitate research and demonstrations of use cases of wearable wireless sensors. A wrist–worn pedometer application was implemented as one of the demonstrations of the capabilities of the platform. In this paper the step counting algorithm is described and the performance is evaluated. The application is targeted for running exercise. However, the detection of steps during walking is also discussed.

Keywords: pedometer, step counter, wireless sensor platform

Medical Equipment Insights 2010:3 1–8

This article is available from http://www.la-press.com.

Introduction

Step counting is a widely used method to assess physical activity. Very simple and cheap pedometer devices are available for any person to wear during running exercise or during daily activities to record the number of steps taken. The benefit of using such a device is mostly the improvement in motivation to increase physical activity. These devices are also used in rehabilitation and disease management. For example, physical activity assessment is important for the prevention or treatment of diabetes.[1] Pedometers have also been used to assess mobility of the elderly.[2]

Pedometer devices are typically worn on the hip clipped to a belt or trousers. The hip is an excellent place for sensing steps as the accelerations there correlate well with steps and the interfering accelerations are small. Another good location for a step counter sensor is on the foot, where even more details, like stride length, can be measured.

The wrist is a convenient place for informative gadgets. It is easy to casually look at the display of a wrist–worn device and one can stay continuously aware of the step counts among other information. However, it is difficult to determine steps from the wrist as there is a lot of interfering acceleration signals from arm movements, which do not always correlate well with the steps taken.

There are wrist–worn step counters on the market today, but there are no public scientific reports on this topic. As algorithm patents are difficult to supervise they are usually kept secret. The Nokia Wrist–Attached Sensor Platform (NWSP) developed in the NUADU project is an open research platform, which has made this publication possible.[3–5]

Materials and Methods

The step counting algorithm uses linear acceleration data from a 3-axis accelerometer sensor. To remove orientation dependency and the earth's gravitational acceleration the sensor signals are processed according to the scheme pictured in Figure 1. Signals a_x, a_y and a_z are the accelerometer signals for each axis

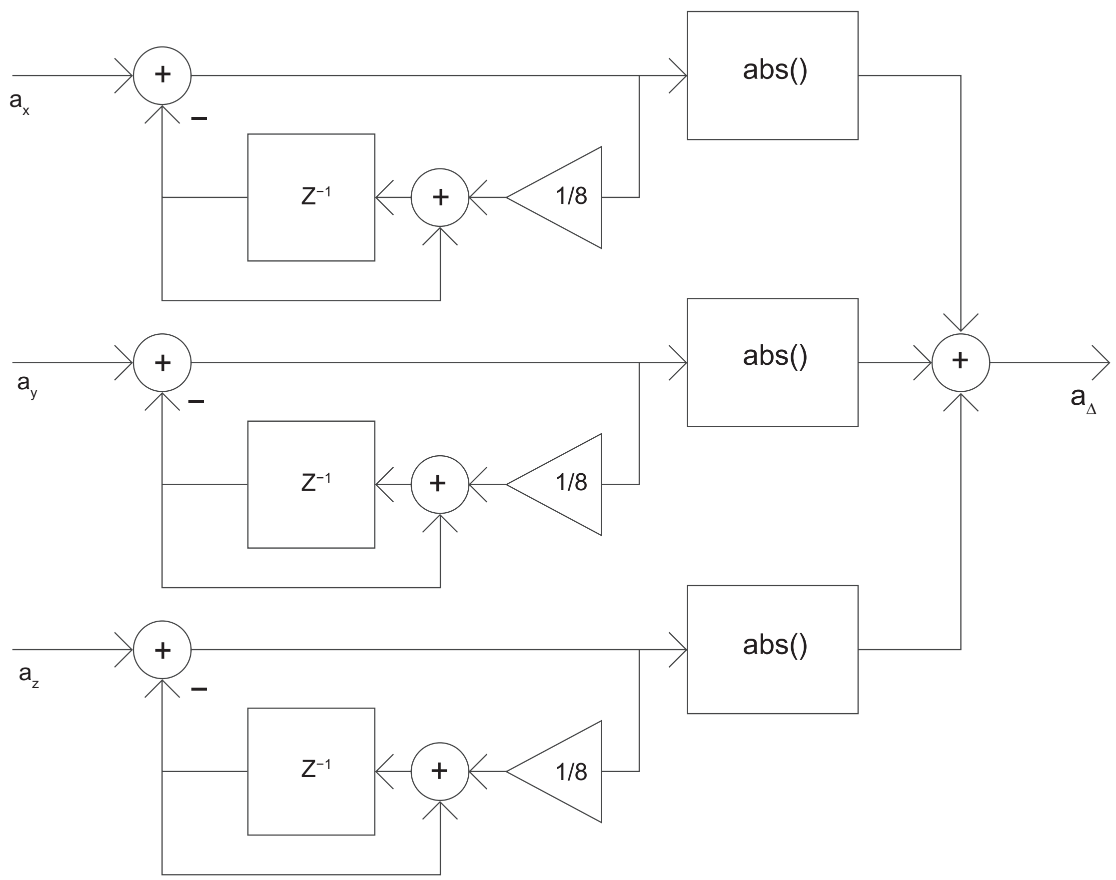

Figure 1. Computing acceleration change value from 3-axis accelerometer sensor signals.

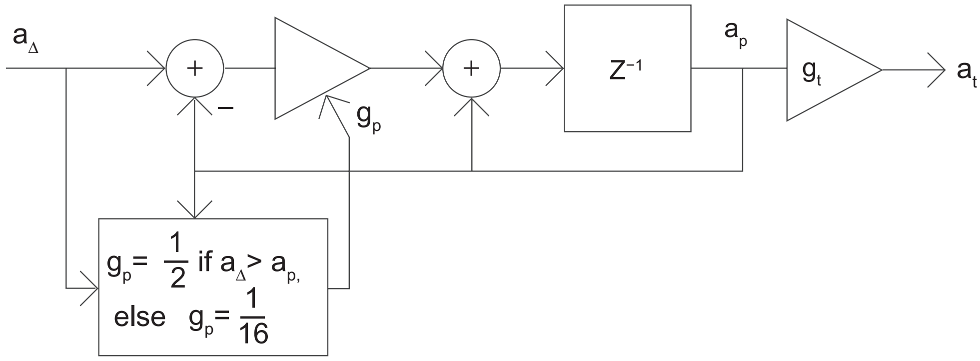

Figure 2. Computing the adaptive threshold level.

respectively. Firstly, each of them is high-pass filtered to remove the static or slowly varying gravitation signal. The filter is implemented by a computationally efficient autoregressive filter of the first degree. Effectively the filter subtracts from the input an integrated value of the output. A gain coefficient of 1/8 is inserted in the loop to adjust the response time and frequency response. The –3 dB cutoff frequency is approximately 1/53 of the sampling rate. The transfer function of the filter is:

$$H_{hpf}(z) = \frac{1 - z^{-1}}{1 + g - z^{-1}}, \text{ where } g = \frac{1}{8}. \quad (1)$$

The three high-pass filtered accelerations are combined to one output signal a_Δ by taking the 1-norm: i.e. summing their absolute values. The 1-norm was chosen instead of the more accurate 2-norm to make the algorithm less computationally intense. The output a_Δ is zero when the device is not moving. Any movement in any direction results in an output signal. With the 1-norm the gain (the scale of the output signal), depends somewhat on the orientation of the device, whereas with the 2-norm the gain is uniform in any direction. However, as the algorithm features an adaptive threshold, it is insensitive to the gain and thus, there would not be any benefit for using the more computationally intensive 2-norm.

To make the algorithm robust, it features an adaptive threshold. This feature makes the algorithm independent of sensor sensitivity and the drift of it. It also makes the algorithm less sensitive to different users and variations in running style and road material. Figure 2 shows the computation of the threshold. It is essentially a peak detector with some slowness added to the reaction time. It is implemented as a low-pass filter of the first degree with a varying response time. The transfer function of the filter is

$$H_p(z) = \frac{g_p z^{-1}}{1 - (1 - g_p) z^{-1}}. \quad (2)$$

In a steady-state case the peak signal a_p equals the input a_Δ because the difference is integrated in a closed loop. The gain coefficient g_p determines the loop gain and a smaller coefficient corresponds to a slower response. However, if the input is greater than a_p the g_p is set to 1/2, which results in a relatively fast response, driving a_p close to a_Δ in a few samples. The step response time to 95% of the final value is 5 samples in this case. If a_Δ is less or equal to a_p the g_p is set to 1/16, which result in a slow response, effectively holding the peak values for some time with a slow decay. In this case the step response time to 95% of the final value is 47 samples.

The threshold value a_t is a fraction of the peak value a_p and is determined by the constant threshold coefficient g_t as $a_t = g_t a_p$. A value of 1/2 has been successfully used for g_t.

The step counting algorithm is shown in Figure 3. When the pedometer application is started the *steps* counter variable and the *holdoff* counter variable are initialized to zero. For each new acceleration sample, if the *holdoff* counter is zero and the a_Δ signal exceeds the threshold a_t, the *steps* counter variable is incremented and the *holdoff* counter is set to value −1. This *holdoff* value puts the algorithm in

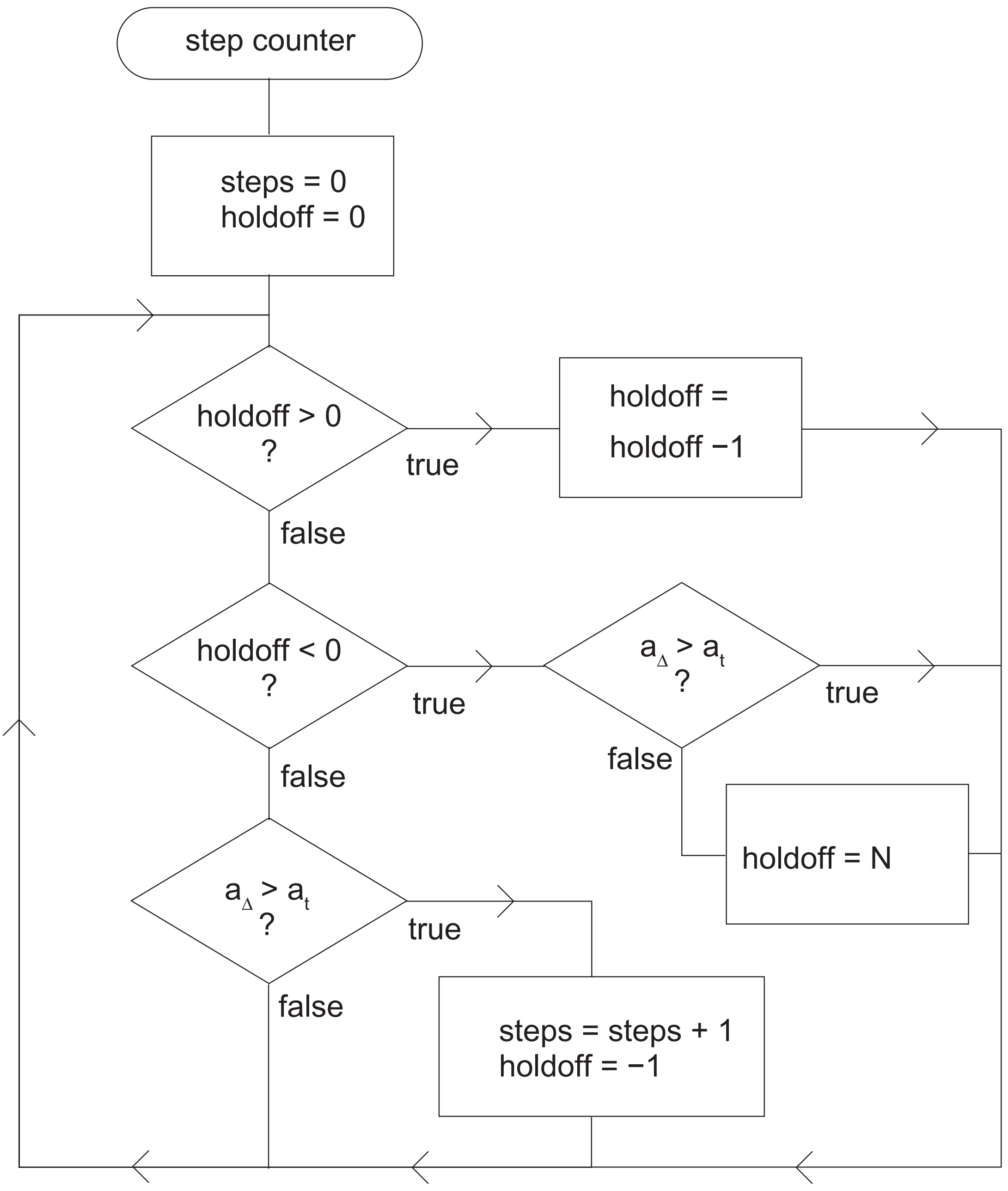

Figure 3. Step counter algorithm.

a state waiting for a sample that is not above the threshold. When this sample has been read the *holdoff* is set to a value *N* greater than zero. If the *holdoff* counter is greater than zero, the algorithm does not count steps but decrements the *holdoff* counter for each sample period until it is zero. The purpose of the *holdoff* period is to prevent superfluous step counts for cases when there is ripple in the acceleration signal. In practice a value of 1 has been used for *N* with success. A value this small works because the ripple is typically small and there are no extra transitions of the acceleration signal across the threshold. Hysteresis could be used instead or in addition to the *holdoff* to improve rejection of noise and ripple. Also, a more advanced algorithm could include smart filtering to reject false step counts. Such filtering typically introduces delays in the display of the step count because several steps must be processed to make a decision on validity. The NWSP step counter avoids advanced filtering to enable an instant display of steps and not to infringe on proprietary technology.

Result

The step counter application was tested and the performance was evaluated. Figure 4 shows a set of acceleration signals for a short segment for one case where a subject was running. The x-axis is in the direction of the tangent of the forearm, the y-axis is parallel to it and the z-axis is perpendicular to it. Normally when a wrist-watch like device is worn tightly on the wrist and the arms are in a position for running, the x-axis of the device points downwards, the y-axis points forward in the running direction and the z-axis to the side. The figure also includes the combined acceleration a_Δ. The case in the figure shows an interesting phenomenon. During the first 4 seconds in the plot there is a strong signal from the x-axis sensor but in the latter part this signal has moved over to the z-axis sensor. The reason for this is that the wrist device has been loosely fitted and has turned around the wrist during the running exercise to the side of the wrist, hanging on the downside of the arm. Each sharp spike in the waveforms of x- and y-axes corresponds to a combination of the heel strike in the gait cycle and the up–down movement of the body.[6] The heel strike signal is strongly softened by body spring–mass system when sensed on the wrist. On the y-axis a periodicity of half the frequency of the other axes can be observed. This is caused by the arm swinging forward and backward with the change in direction happening on each step. This example shows that at least a sensor with two axes is needed to cover situations where the wrist device might turn around the wrist. As can be seen in the plot, the a_Δ signal is insensitive to the change in the device orientation and has a fairly constant periodic acceleration signal with each step clearly distinguishable.

Figure 5 shows a plot with the adaptive threshold a_t together with the a_Δ and a_p signals. It can be observed that the slow reaction time of the peak detector evens out the differences in acceleration peaks making the threshold signal smoothly ripple around an average level despite occasional high acceleration peaks. The area painted in grey is where the a_Δ signal is above the threshold and steps are detected.

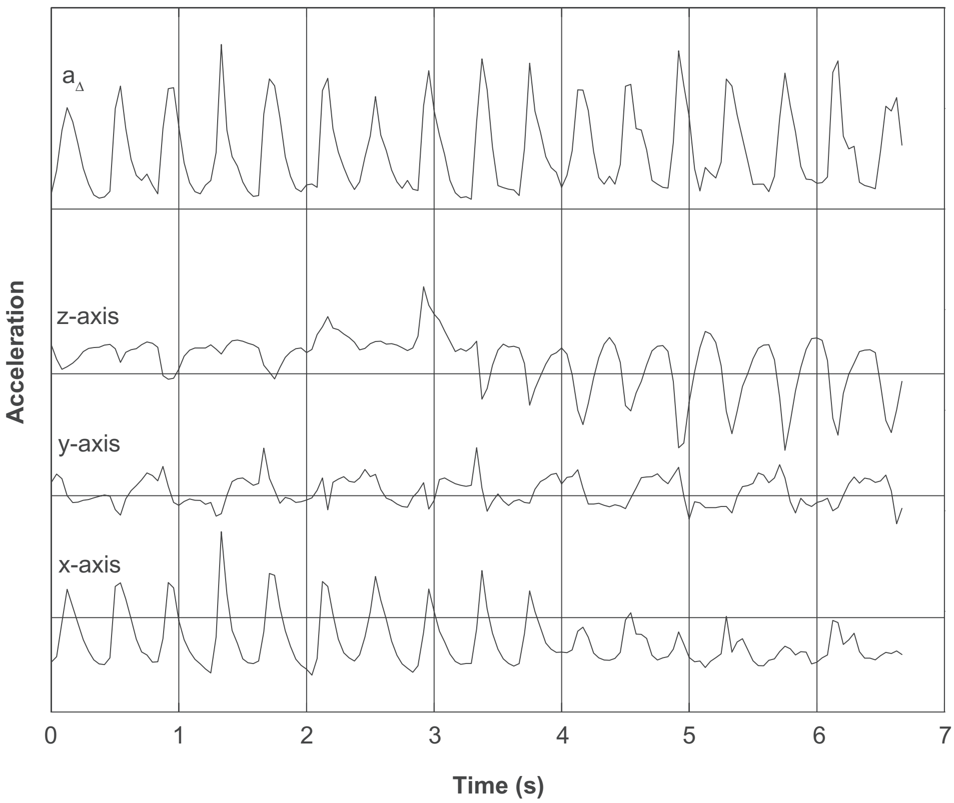

Figure 4. Acceleration signals during running.

The NWSP pedometer demo application was intended for running exercise. Tests showed that the application does not count steps during walking. Figure 6 shows the acceleration signals from the wrist during a walking exercise. The signals are very noisy and have low amplitude. From the z-axis signal some periodicity can be observed. This periodicity is caused by swinging motion of the arm and thus, the frequency is half of the step rate. The combined acceleration signal a_Δ has lost an obvious periodicity because noisy signals from x- and y-axes have been added. This makes it difficult to detect steps. In the plot around 10 seconds on the time line there are some disturbances corrupting the periodicity in axis z. This is a typical sporadic arm movement that occurs frequently while walking, making accurate step counting from the wrist very challenging for any activities other than running.

A comparison was made against Nokia Step Counter application running on a Nokia N95 mobile phone as a reference. This application is believed to be very accurate and it is available for free from Nokia beta labs.[7] A small number of test users ran with the NWSP pedometer on the wrist and the N95 device in the pocket simultaneously counting the steps during short exercises of a few hundred steps. Results showed that the NWSP step counter acquired consistently around 30% fewer steps than the reference. This result was surprising as the contrary was expected. As there is no advanced filtering for rejecting false steps and no hysteresis to reject ripple and noise, it was expected that extra steps would be acquired by the NWSP. Also having a very low hold–off period could be expected to pass through some extra steps.

Discussion

Measurements of accelerations from the wrist showed that steps can be identified from the acceleration signals. From running exercises the detection is very clear. From walking activity steps could be detected with some limited accuracy using proper algorithms. The NWSP step counting algorithm was designed for running exercise. This was done before

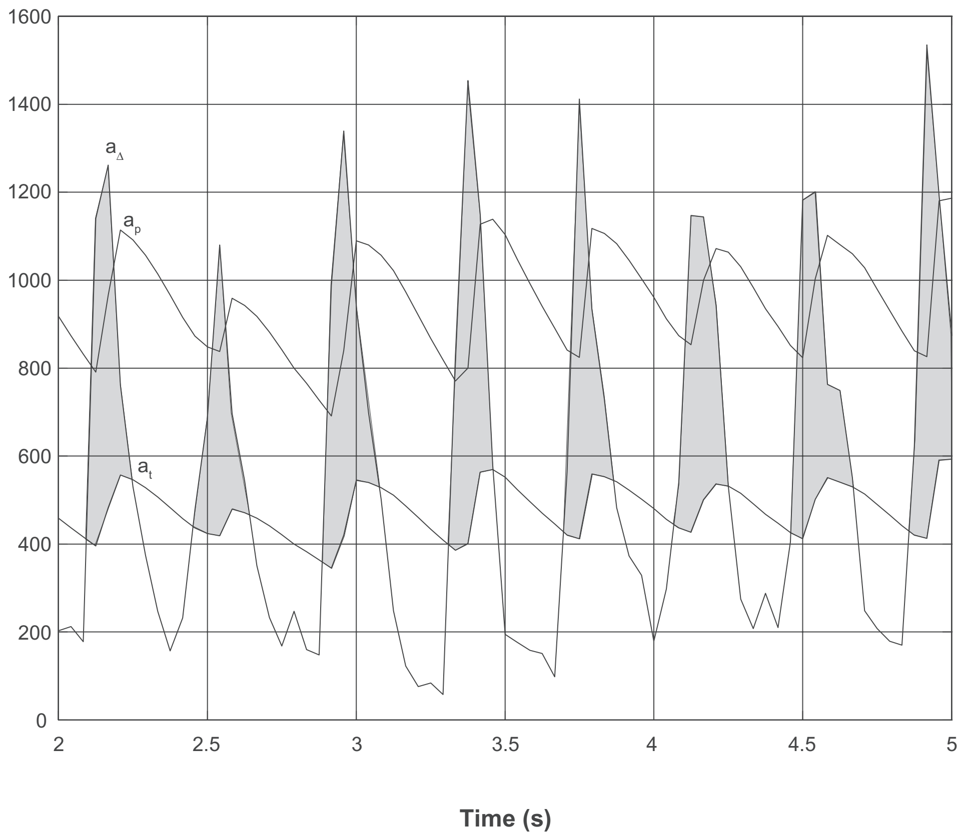

Figure 5. Generation of the adaptive threshold signal.

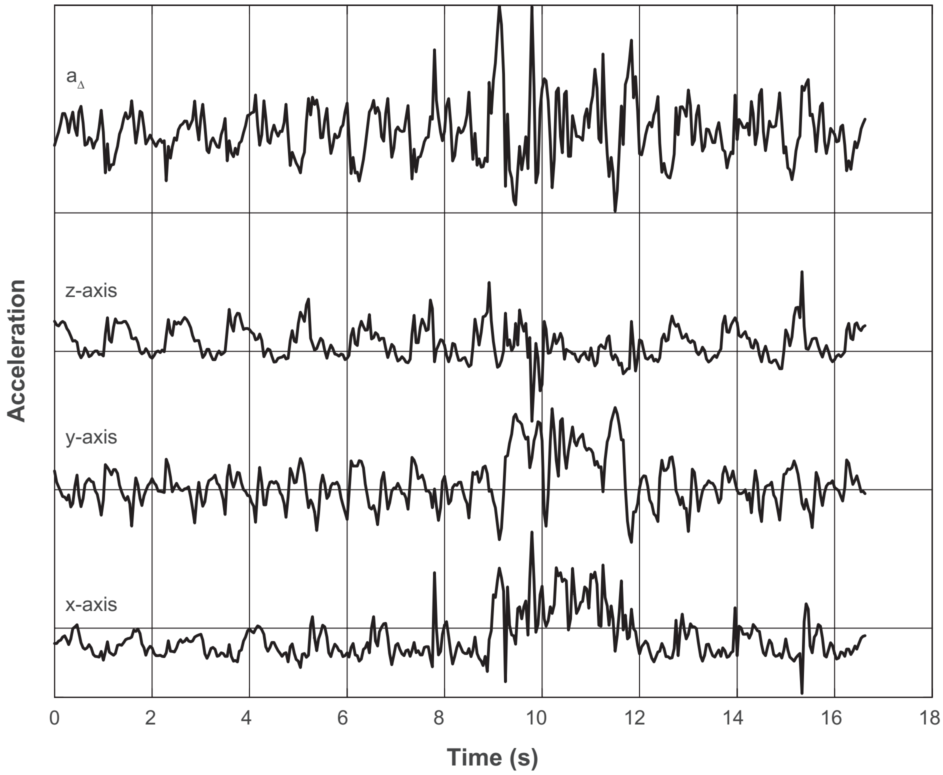

Figure 6. Acceleration signals during walking.

the acceleration measurements were available and it was later verified to be functional in laboratory conditions. However, the real running test showed a significant loss of steps. The probable cause of loss of steps lies in the way the 3-axis accelerations are combined into one acceleration signal a_Δ. The sum of absolute values of the individual axes of acceleration may stay above the threshold a_t for a long time if there is interfering accelerations present from swinging arms, for example. Thus, steps are masked out by this interference. The problem could be remedied by raising the cutoff frequency of the high pass filters. As arm swinging has lower frequency accelerations than caused by the step impact it may be attenuated by the high pass filter. Another solution is to continuously monitor each acceleration axis separately and only use the one with clearest periodical signal as the source for step counting.

Reviews of pedometers have revealed very high inaccuracies in available devices based on acceleration sensors.[8] To improve accuracy alternative sensing methods have been suggested, such as gyroscopes.[9] As the NWSP includes gyro sensors, they could be utilized to improve the NWSP pedometer. Gyros are insensitive to linear acceleration and thus, interfering accelerations are suppressed. However, the heel strike or body up–down movement can not be detected by this kind of sensor and the algorithm would have to rely on detecting arm swing.

Step counting from the wrist is an interesting topic. This exercise has shown that it is indeed possible but also it was shown that there are challenges. The NWSP step counter is functional but somewhat inaccurate. Improvements are possible and they have been identified during this work.

Disclosures

The manuscript has been read and approved by all authors. This paper is unique and is not under consideration by any other publication and has not been published elsewhere. The authors report no conflicts of interest.

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