Inertial Measurement System for Human Gait Analysis

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ABSTRACT
An inertial measurement system is described in this study. In the first part of the paper history and gait cycle terminology are described and a relevant research is made. The system is used for an analysis of human gait and determination of its major parameters. Several inertial measurement units (IMUs) are attached to subject's feet. The program is used to analyze original signals from the IMUs. The analysis algorithm is described in detail. Performed experiments and the ways the data were analyzed are also described. The paper also includes the statistical estimation of the data.

Categories and Subject Descriptors
I.5.4 [**Pattern Recognition**]: Applications – Signal Processing, Waveform Analysis

General Terms
Algorithms, Measurement

Keywords
Gait analysis, Human gait, Filtering

1. INTRODUCTION
1.1 History
IMUs and accelerometers are used in medicine practice to determine several physical parameters in order to make diagnostics. Such diseases as cerebral palsy, arthritis of the hip, the aetiology of some sports injuries, abnormal back movements [5] could be recognized and examined with the method described in this study.

First clear description of human gait cycle was given in 1836 by Weber brothers (Germany) [12]: they used only a stopwatch, measuring tape and a telescope. They were also the first to illustrate the alignment of the trunk and lower limbs at 14 instants during the gait cycle (Figure 1) [3].

First attempts to use accelerometers to measure human movements were made in 1953 [9], but accelerometers were expensive and unreliable at that time, so it wasn't rational to use them for a medicine practice [6]. J.R.W. Morris [8] referred to using accelerometers in 1973: he proposed recording of an accelerometric data on a portable subject-carried tape recorder or passing the data by a lightweight cable to a fixed recorder. In that study an analysis of data was done on a small digital computer. The data were sampled at 10ms intervals and digitized; cursors were set to beginnings and ends of cycles. The signal was also filtered to remove a drift and to set a lower frequency limit on the signal pass-band.

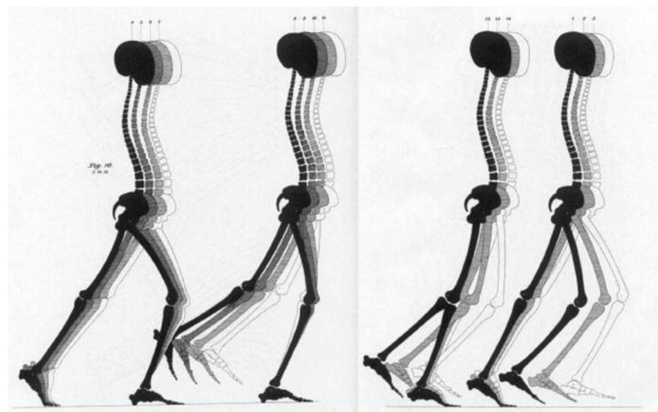

Figure 1. The alignment of the trunk and lower limbs at 14 instants during the gait cycle (Plate XIII, Weber and Weber [12]).

1.2 Relevant research
Several types of measurement systems are used to analyze human gait. Inertial motion measurement systems have advantages over them.

Video-based motion capture (mocap) systems use cameras and special markers to locate points on an object. Although such systems provide exact information about movements, they are fixed to a certain environment and need specially trained personnel to operate with. Normal daily activities can't be accurately captured by such systems.

Wearable inertial measurement systems are used to perform real-life tests in unequipped environments. Such systems are rather compact and mobile, so can be quickly installed and easily used.

A lot of inertial measurement systems are available on the market. Xsens provides different inertial motion capture solutions, including Xsens MVN system [13], which can be used for gait analyzing. But according the excess number of sensors, which would be used for a simple gait analysis (several accelerometers, gyroscopes and a magnetometer in each inertial measurement unit), the total price of the measurement system is very high (more than €5000) and this excessive functionality is not justified.

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Shimmer wearable sensor system [11] provides equipment, supporting tools and applications for all stages of signal processing. Shimmer wearable sensor platform and equipment allow simple and effective biophysical and kinematic data capture in real-time. One sensor includes basic motion sensing, micro-controller to set up data capture, radios for wireless transmission of data, memory for local storage of data, and a rechargeable battery. The units have open source firmware that allow the units to be configured specific to each applications data capture. So, RAW data can be easily gathered with these sensors, but Shimmer doesn't provide any solution for gait analysis: an algorithm and a program should also be developed.

2. GAIT CYCLE TERMINOLOGY

Terminology widely used to describe human gait was developed at the pathokinesiology laboratory of Rancho Los Amigos Hospital [1]. The terminology defines eight functional phases of a gait cycle.

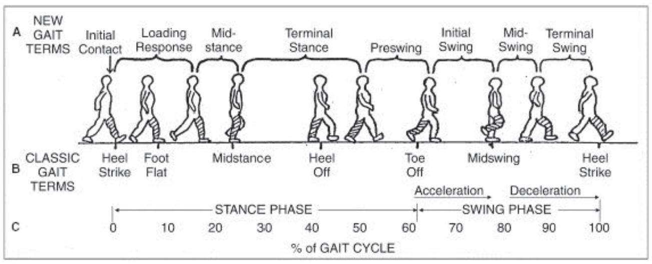

Figure 2. Gait terms and normal distribution of time during a gait cycle (Illustration courtesy of Carson Schneck, M.D.) [10].

A gait cycle applies to movements of a single foot during human gait. One cycle is a period between two nearest moments when a foot touches the ground. Each cycle begins with a **stance phase** and ends with a **swing phase** (see Figure 2). During the stance phase a limb is in contact with the ground. During the swing phase the foot isn't in contact with the ground: only the opposite foot touches the ground. The ratio of durations of stance and swing phases is about 3:2 (60 and 40 percent of a single gait cycle) for normal human gait [7].

Two periods of double limb support can be distinguished in a single gait cycle. The first period begins with the gait cycle itself (at the stance phase) and lasts for 10 to 12 percent of the cycle. The second period is located at the end of the stance phase and lasts similarly for 10 to 12 percent of the gait cycle. Thereby two periods of double limb support take from 20 to 24 percent of the total gait cycle. Periods of double limb support alternate with periods of single limb support.

A stance phase can be divided into four periods: loading response, midstance, terminal stance, preswing.

Loading response starts with the initial contact – a moment, when a foot touches the ground, and ends with a beginning of the single limb support period, so loading response is actually the first double limb support period.

Midstance follows after a moment the opposite extremity begins to swing and ends, when the center of gravity of the whole body is over the foot.

Terminal stance, the next period of the gait cycle, ends when the opposite extremity contacts the ground.

The stance phase ends with **preswing** period, which begins when the opposite extremity contacts the ground. Preswing ends when the toe gets off and takes about 60 percent of the stance phase, so this period is actually the second double limb support period.

A swing phase is divided into three periods: initial swing, midswing and terminal swing.

Initial swing begins when the foot gets off the ground and ends at a moment of maximum knee flexion.

Midswing lasts till the tibia becomes vertical. **Terminal swing** finishes the gait cycle; the end of this period matches to the initial contact.

3. EXPERIMENT

3.1 Goals

The goal of this study was to develop an algorithm and a program to merge the data from IMUs with actual parameters of human gait. The key moments to evaluate from signals were chosen as moments when a heel strikes and a toe gets off the ground. Due to the fact the data from two legs come synchronously and a common time scale applies to each IMU, the following phases were planned to be distinguished:

- average durations of a gait cycle (or stride frequency),
- stance and swing phases for both legs with comparison to each other,
- duration of double and single limb support.

3.2 Participants

The gait data was gathered from 7 healthy subjects both male and female (25, 21, 22, 30, 58, 58 and 60 years old, 60 to 99 kg weight, 153 to 178 cm tall). Two to three data sets were collected from each subject.

3.3 Instrumentation

Figure 3. IMUs, used in the study.

The data were collected using 4 IMUs (see Figure 3). Each measurement unit includes a triaxial accelerometer ADXL345 [2], ATMega8 controller, class 1 Bluetooth module. The Bluetooth signal is transmitted to a desktop computer (Intel Core i3 CPU 3.20GHz 3.20GHz, 8GB RAM, Windows 7 x64) and written into a text file by special program. Each text file has 12 columns: three projections of apparent acceleration times four (the number of IMUs). Frequency of gathered data is 100 Hz.

3.4 Data gathering

Figure 4. A part of a video frame, captured during the experiment.

Figure 5. A scheme of IMUs' placing on a foot.

Each subject's demographic data was collected. During experiments subjects were barefoot. Sensors were turned on and then were fixed on a subject before each experiment. The sensors were placed on a heel and a toe of each foot (Figure 4, Figure 5). Four pieces of stretching elastic tape with several pins were used to fix the sensors on the body rather rigidly.

After the beginning of data collecting subjects were asked to stand still for 5-10 seconds. Then they were asked to do 6-8 steps in a straight direction keeping up their usual tempo and to stay still for 5-10 seconds after the walking. After each passage the data gathering was stopped and the data was written into a separate text file. Data from each subject were recorded twice.

Each recorded signal has three notable regions. The first region, where a subject stands, has almost constant values: just the gravity and noises caused by spurious accelerations (vibration, etc) and slow movements of soft tissue and IMU itself. The second period begins with steps that a subject does and concerns gait cycles. The gait parameters are extracted from this period. The third period corresponds to a period, when a subject stands after the second period. The calibration data (a value and direction of gravitational acceleration) are extracted from the first and the third periods.

4. ESTIMATION OF THE DATA

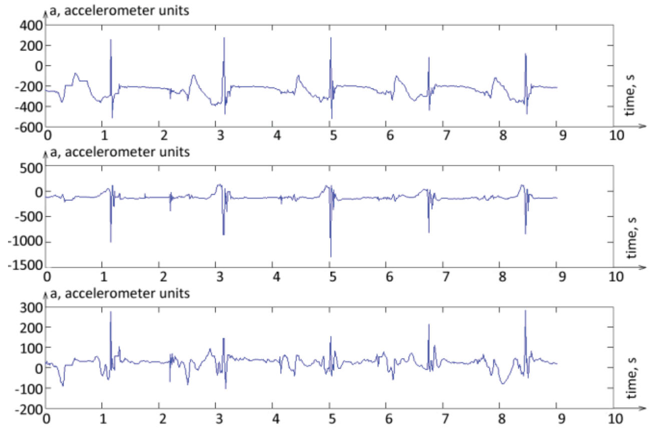

Figure 6. A sample of an original signal.

Figure 6 shows a part cut from an original signal, gathered from one of the IMUs.

Gait is a cyclical process, so the signal can be considered as a repeated signal. At the same time each gait cycle is unique as a subject is exposed to many factors.

Data from each sensor are split into cycles, which are superposed and aligned to the local maximum generated corresponding to the second foot contact with a floor. Figures 7 and 8 illustrate repeatability of the signal gathered from the sensors from cycle to cycle (data from one experiment). Absolute value of the acceleration is used for the analysis of the signal (instantaneous value of the apparent acceleration); each graph shows about one and a half of the gait cycle. These graphs show similarity of the data for each cycle step. The data was obtained from all the considered devices.

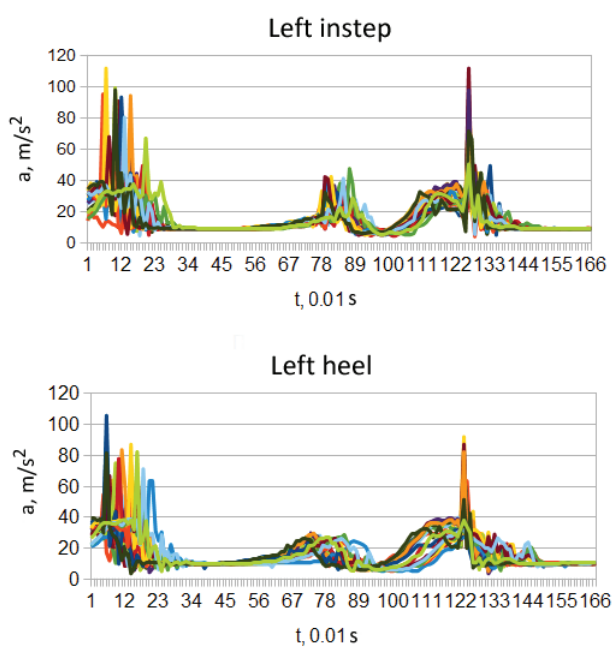

Figure 7. The illustration of signal repeatability for a left foot

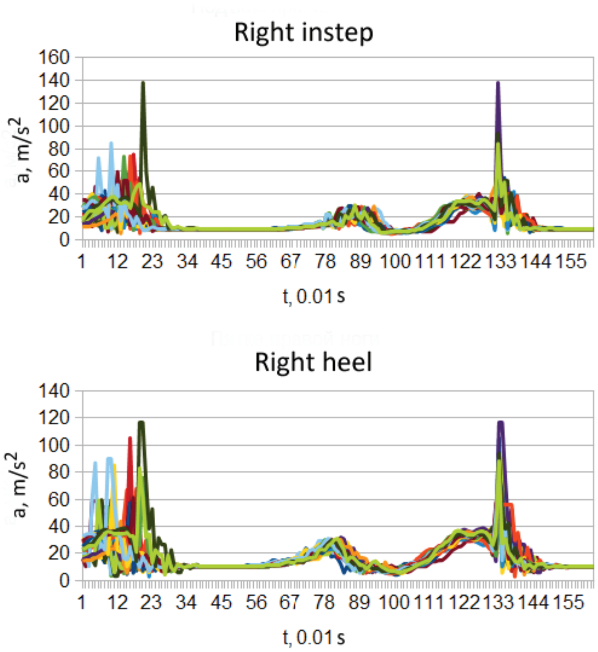

Figure 8. The illustration of signal repeatability for a right foot

The goal of statistical estimation is to determine which reliable parameters can be extracted from a signal.

Root mean square error value (RMSE) of a step period shows small variations of the period (Table 1). Consequently, the step period can be determined using the IMUs.

Variations of local maximum values (absolute values) were also investigated (Table 2). In theory it is possible to describe the shock during a contact of a foot with the surface. According to the obtained values of the distributions and dispersion, it was concluded that the instantaneous values of the local maxima at a given sampling rate (100 Hz) are not suitable for gait analysis.

Table 1. The mean value and RMSE for the duration of the step

Device mounting place	Mean, s	RMSE, s
Left heel	1.117	0.044
Left instep	1.145	0.040
Right heel	1.202	0.050
Right instep	1.204	0.048

Table 2. The mean value and RMSE for the values of the step local maxima

Device mounting place	Mean, m/s^2	RMSE, m/s^2
Left heel	53.72	22.77
Left instep	61.59	24.41
Right heel	77.90	16.32
Right instep	66.93	21.77

5. ALGORITHM

5.1 General steps

Several steps to analyze discrete data are proposed:

1. The choice of the proper coordinate system for a signal from each IMU. Due to the fact what sensors are fixed in an arbitrary orientation, three projections of the signal differ in every test. Two methods were developed to rotate the signal's coordinate system.
2. Normalization of signals. Data scale of a signal, gathered from accelerometers, varies a bit from device to device. To behold proper values the signal should be converted to the SI units (m/s^2).
3. Segmentation. Recognition of single gait cycles. Distinguishing stance and swing phases from the signals.
4. Merging data, collected from signals.

5.2 Changing the coordinate system

Two requirements are made to a new coordinate system:

- The gravity vector should be directed straightly down (in the opposite direction to the Z-axis).
- A transformed signal should be minimal in one of the projections (a second projection was chosen). If we assume that the every movement of subject's feet is made in a sagittal plane, this projection of the signal contains only noise. The human gait is not strictly placed in the sagittal plane, but this assumption is justified as the first projection of the signal represents more contrast data and the second, "noisy", projection contains values, 2-4 times less than the values in the first projection.

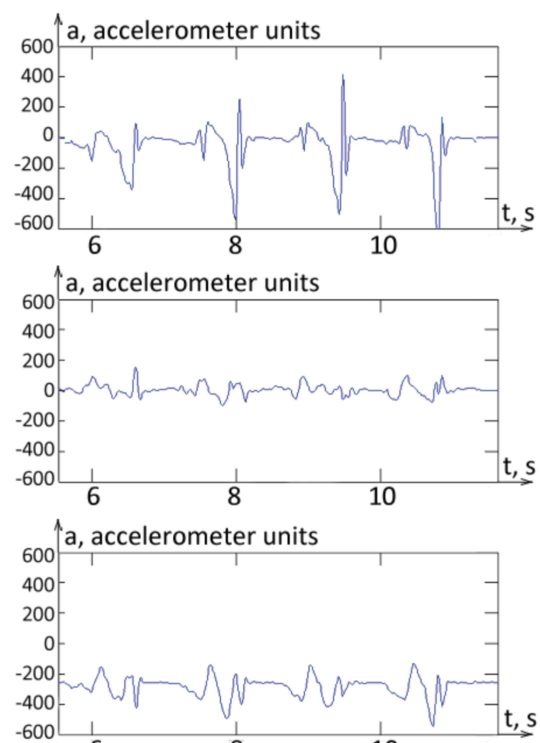

Figure 9. A sample of a transformed signal.

A typical sample of a transformed signal is shown on Figure 9. Amplitude of the second projection is clearly less than two other projection amplitudes and not so periodic.

5.3 Signal normalization

Sensitivity of the IMUs equals 256 units/g [2], so one “accelerometer unit” of the original signal equals about 0.04 m/s^2. A following method was chosen for signal scaling: defining intervals where a subject stands still, approximating parts of the signal in such intervals and multiplying the signal on 9.8, simultaneously dividing to the approximated value. At this point we assume gravitational acceleration to be 9.8 m/s^2 and get the resulting signal in the International System of Units.

5.4 Signal segmentation, merging data

First step to signal segmentation is estimating mean step duration.

The autocorrelation function is defined as

$$\Psi(\tau) = \int f(t) f(t-\tau) \mathrm{d}t$$

and is used to find repeating patterns in a signal. By applying this function to the original signal an autocorrelation graph is drawn (Figure 10). The mean step duration equals the X-coordinate of the second local maximum on this graph (not including the local maximum at x=0). This is often the highest peak, but not always: in 1 of 16 data sets the highest local maximum was the fourth significant maximum from the left.

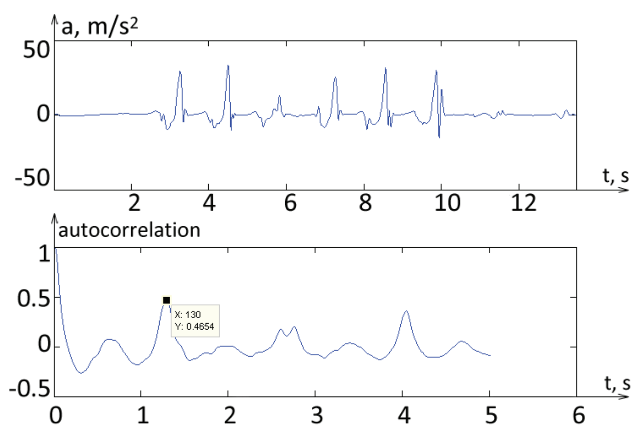

Figure 10. The original signal and the autocorrelation graph.

To distinguish stance, swing phases, periods of double and single limb support the following moments should be extracted from a signal timeline: both feet’s heel strikes (HS) and toe off events (TO). Stance phases of each foot are located between HS and TO moments, swing phases are completely opposite. Double and single limb support periods are extracted from the whole gait cycle: each cycle contains two double limb support periods located on a crossing of each foot’s stance phases.

According to [4] the considered gait events are to be detected as follows:

1. HS is detected as the time of occurrence of the nearest main peak of the vertical heel acceleration (i.e. the Z-axis signal of the heel accelerometer) before the beginning of the heel flat zone.
2. TO is detected as the middle of the time interval surrounded by the end of the toe flat zone and the first main positive peak of the vertical toe acceleration (i.e. the z-axis signal of the toe accelerometer).

So every swing and stance phase, double and single limb periods can be allocated by finding the following gait events: HS and TO.

6. PROGRAM

The algorithm described in Section 5 is implemented in a program to cooperate with a user through a plain user interface.

Input data: a text file containing discrete data gathered from four IMUs. The program can also be tuned to use other number of devices.

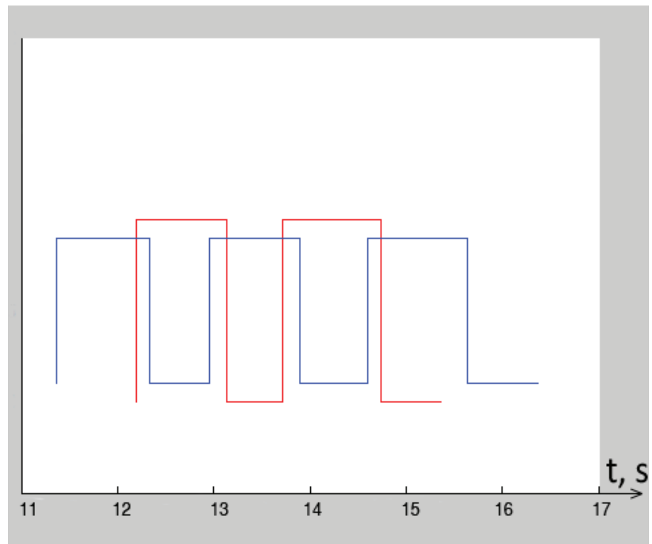

Figure 11. A sequence diagram of the subject's gait.

Output: the program creates two windows. First window contains a sequence diagram of a subject’s gait (Figure 11). A blue line (begins first) on the diagram refers to a left foot of a subject (this can also be a right foot – it is adjustable), red line – to a right foot. Horizontal axis is a timeline in seconds. Each point in the line can reside in two positions: upper and lower. These positions represent stance and swing phases respectively. Double limb support periods are observed in intervals, where both curves have

Different values on the vertical axis for each curve are applied just for comfortable view of the figure on black and white outputs. Each significant point on the diagram can be easily observed, so every calculation is easy and visual.

	Mean, ms	RMSE, ms
Step duration	1278.3	51.5
Swing phase (left)	525	41.2
Swing phase (right)	483.3	25.2
Stance phase (left)	778	57.2
Stance phase (right)	792.5	58.5
Double limb support	133.8	40.7

Figure 12. The major parameters of the gait.

Second window (Figure 12) represents information on the subject's gait: mean step duration, mean duration of swing and stance phases (for both feet) and mean duration of the double limb support period. A RMSE value is shown along with every mean value.

7. CONCLUSIONS

Some facts from the history of the gait analysis and accelerometer applications were observed. Two existing inertial measurement systems were reviewed.

The inertial measurement system is a combination of 4 IMUs and a program, which is a realization of a developed algorithm. The ordinary gait terms were examined.

Several experiments were performed. Gathered data were statistically estimated and methods of the signal analyzing were chosen.

The developed algorithm and used methods are described in detail in Section 5. The program was written to provide a simple interface to a user.

The program provides sufficient accuracy and can be used in a medicine practice.

8. ACKNOWLEDGMENTS

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