Inertial Sensors and Wavelets Analysis as a Tool for Pathological Gait Identification

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Abstract. The human gait analysis by using wavelets transform of signal obtained from six inertial ProMove mini sensors is proposed in this work. The angular velocity data measured by the gyro sensors were used to estimate the translational acceleration in the gait analysis. As a result, the flexion - extension of joint angles of the knees were calculated for healthy people and with impaired locomotion system. After measurements we propose to use one of wavelet transform (wavelet type) in order to analyze the signals, indicate a characteristic feature and compare them.

Keywords: Human gait · Inertial sensors · Wavelet analysis

1 Introduction

Gait analysis is a clinical tool for obtaining quantitative information of the gait of a person to diagnose walking disabilities [5,6]. Common methods of gait analysis include using cameras to track the position of body by using reflective markers. Although this conventional system has been utilized successfully in many research fields, such as sport and clinics, it is limited to the laboratory work space required by the camera [7]. An alternative is to use acceleration and angular velocity data measured from inertial sensors attached to the body. Miniature inertial sensors are steadily gaining interest because of their limited power consumption, low cost and good user compliance when they are embedded in wearable sensor systems or portable devices [2]. Currently several applications in human motion analysis may benefit from miniature inertial sensors [1,12]. Human body motions are captured and measured, next inertial data from IMUs are transmitted to computer via Bluetooth. Then data are processing because this method does not directly measure position. A major challenge is to translate these data into meaningful three dimensional positional data, such as the joint angles of hip, knee and ankle. The differences between lower limbs can be used for evaluating symmetric gait or some of disorders.

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2 Wireless Sensing System

The sensing system is composed of six body area wireless inertial sensor nodes based on ProMove mini platform [13]. The system creates the bridge between inertial measurements units and wireless sensor networks. It is embedding in one device the following: 10 degrees-of-freedom inertial sensors: ±2 to 16 g accelerometer, ±250°/s to 2000°/s gyroscope with resolution 0.007°/s and ±250°/s range and magnetic field intensity (compass), 2 GB flash memory in each sensor, low-power RF transceiver in the 2.4 GHz license-free band. Inertia gateway as a central hub for synchronized data collection <100 ns. Battery life 4 h in full streaming mode.

The ergonomic design of ProMove-mini allows for easy strap attachment and body mount. Each sensor unit is 51-46-15 mm with weight 20 g (including battery). The Inertia Studio software enables real-time visualization of sensor data, as well as over-the-air reconfiguration of the sensors and wireless parameters. All data retrieved by the Inertia Studio software is logged for post-analysis. As shown in the Fig. 1, the ProMove mini sensors are placed on the part of body along the right and left leg on the thigh, shank and foot. In global coordinate system (green color) the x-axis is the walking direction, y-axis lateral direction and z-axis opposite direction of gravity. For each sensor the orientation is calculated relative to Earth reference frame in terms of roll, pitch and yaw angles. By combining the orientation of each node, we obtain the joint angles.

By using four quaternion parameters q_0, q_1, q_2, q_3 obtained from the investigations carried out in this work, we calculated the Euler angles of each node as follows

$$\theta = \arcsin\left(2(q_0 q_2 - q_3 q_1)\right) \tag{1}$$

where θ means rotation about y-axis.

3 Experiment

The main objective of our experiments is to validate the knee angle in sagittal plane and wavelet analysis of human gait. To achieve these objectives, we focus in the experiments on the following tasks:

- prepare the patient for testing (interview about the illnesses locomotor) and connect the gateway to the computer and sensor parameter settings (sampling 200 Hz);
- mount the sensor as shown in Fig. 1, turn sensors on and verify that data is received from all of them;
- standing starting position for the examination of the patient;
- resetting the button resets the algorithm used for calculating the orientation. After resetting, it is necessary hold the nodes still for a few seconds to stabilize their orientation;
- start recording (patient goes) and stop recording;

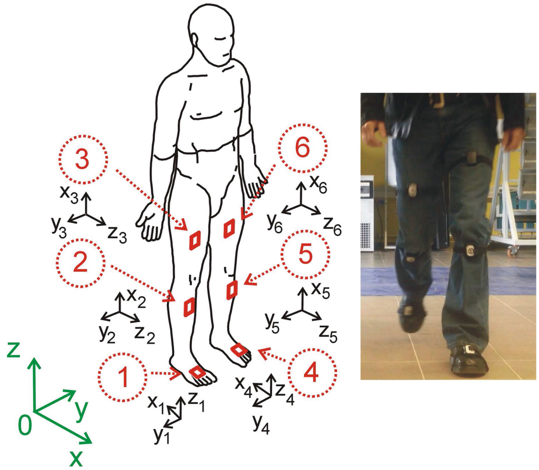

Fig. 1. The human model and coordinate systems. The x, y, z coordinates represent the global coordinate system, the x_s, y_s, z_s represents the sensor coordinate system (a), subject wearing the ProMove mini nodes (b)

- collect all the raw data from all sensors to a central computer via the USB (by using wireless system at the highest possible data rate there is packet loss). Therefore packet loss can be avoided by enabling flash logging and downloading the logs after the experiment (via USB cable is faster);
- process the data on the computer and marking the beginning of each of the left and right step and calculation of the knee angles for the left and right leg as the arithmetic mean of several steps;
- data transformation into gait cycle and plots and wavelet analysis.

In the Fig. 2 the knee average flexion of left and right leg a health person in sagittal plane it is shown. The man 44 years old, 176 cm height and 76 kg weight. The angles were calculated by divided data into steps. Each step was interpolated, because there was different number of samples. The mean angle of right and left knee was transformed to the cycle. It is noted a slight difference between angles in loading response and swing (approx. 3°). In the left leg in stance phase there was noticed the characteristic change in flexion angle in 13–15 % of cycle, whereas in the right leg this phenomenon does not occur.

The 42 years male patient complaining of paralysis of the left foot limb. A study of MR spine lumbosacral. The smoothing lumbar lordosis and multilevel changes distort the intervertebral joints were determined. The symptoms of degenerative disc disease L4/L5/S1 with central protrusion disc m-k L5/S1 entailing root compression, and the center-left-sided disc protrusion m-k L4/L5 adjacent to the left L5 nerve root in the spinal canal. The conclusion was: The symptoms of lumbar disc L4/L5/S1, the more the left hand side at L4-L5 (Fig. 3). The disc herniation caused stretching and inflammation of an overlying nerve root. It also caused the leg pain, numbness and tingling and weakness in the

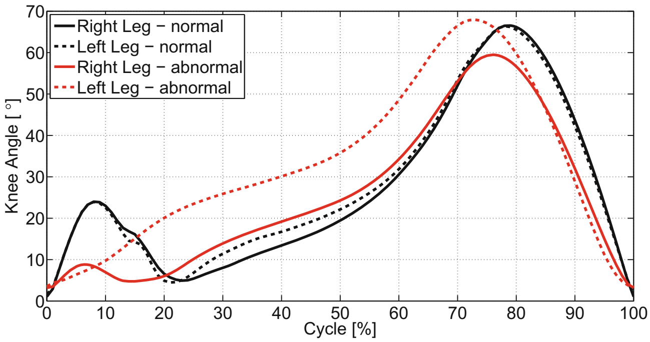

Fig. 2. Knee angles during a normal and abnormal gait

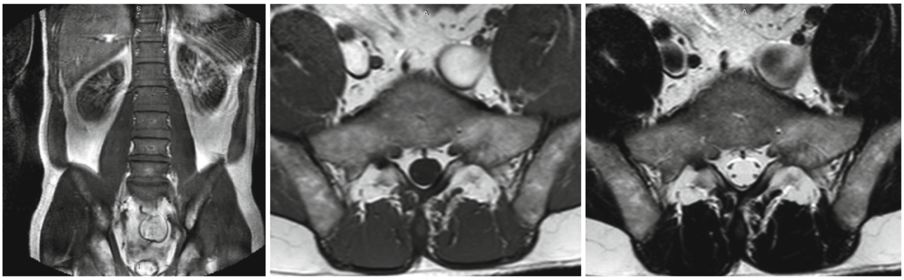

Fig. 3. The patient spine magnetic resonance-data from own sources

distribution of the nerve root. In the Fig. 2 red curves show knee angles in case of abnormal gait. The disc herniation caused stretching and inflammation of an overlying nerve root. It also caused the leg pain, numbness and tingling and weakness in the distribution of the nerve root.

4 Wavelet Analysis

The sensors transfer an acceleration signals, among others. The signals consist of three components related to three directions of Cartesian coordinate system of each sensor. The sum of the components is taken into consideration as analyzed signal, which describes the movement of the part of a leg. The signal includes acceleration of gravity. Because the human gait is characterized by periodicities and simultaneously some characteristic periods may occur in specific time periods, the wavelet tool is chosen. The advantage afforded by wavelets is the ability to perform local analysis. Because wavelets are localized in time and scale, wavelet coefficients are able to localize characteristic changes or differences in analyzed signals [3,4]. By shifting parameters of wavelets, they can be applied as a focus directed to interesting signal area described by time and scale related to frequencies.

Here it is introduced an algorithm combining discrete Fourier transform (DFT) and continuous wavelet transform (CWT). It applies DFT of the signal in first step and next the same transform of the analyzing wavelet at the appropriate angular frequencies in order to obtain directly comparable scales. In the next step the algorithm takes the product of the signal DFT and the wavelet DFT over all scales found. Eventually, it inverts the DFT to obtain the CWT coefficients. This procedure easy allows to convert wavelets scales to frequencies, precisely to so-called pseudo-frequencies. These pseudo-frequencies represent, not the exact frequencies, but some frequency ranges. But the most useful in the case of wavelets analysis is an ability of filtering and in the same time reconstruction of signal in the chosen range of scales. The Morlet wavelet is the analyzing wavelet in the using algorithm [8,9,11]. The conducted analysis shows some particular features of the human gait, which are not possible to observed in raw signal. Look out for important symptoms of human gait may be difficult as well in raw signal. The example of analysis of one step during a gait health person, for the sensors number 2 and 5 placed on right and left leg, is shown in Fig. 4.

In the Fig. 4a, b it is shown the analyzed signal and the signal after reconstruction by using inverse wavelet transform. These analyses are conducted in the case of normal gait i.e. during health person walk. In the upper row of figures one can see at first measured and next reconstructed signals (red curves), respectively for right and left leg. Both signals look like to be the same, which indicates that the wavelet transform does not cause any loss of information when it is conducted in properly width range of scales. Additionally in first figures for each leg in the upper row, blue curves show the signal which is reconstructed for chosen, limited range of scales. These limited range is considered as the part of the signal represents main feature of each leg movement during one step. In these figures (Fig. 4a, b) in the middle row, in first figures in case of each leg, there are absolute scales values (modulus) of wavelet coefficients shown. This kind of analysis, in a form of bands seen in these figures, may deliver details about components of a gait characterized by constant periodicity (frequencies), having variation similar to harmonic functions, for instance sine function. In the next figures there are shown real parts of wavelet coefficients, which precisely shown the periodicity. In the side legends of these figures the values of coefficients change from positive maximal to negative minimal values in the clearly seen areas in these particular figures. The area approximately between 0.24 and 0.49 scales values along whole time axis indicates constant pace of human gait. The character and variation of this pace, confirm the harmonic components, which is clearly seen in sides figures at the appropriate scales level. The other area is in the range of lower scales, at scale levels approximately below 0.24 value. First area up to about 0.25 ms is related to steps periods, when the human foot, at first moment a heel and next a mid-foot, take a contact with a floor and next it is lifted above. This period of step is represented in first 20 % of pace cycle, shown in Fig. 2 and characterized by appropriate knee angle changes. Next looking along the time axis at these figures, there is the another region that shows a moments, when a body weight

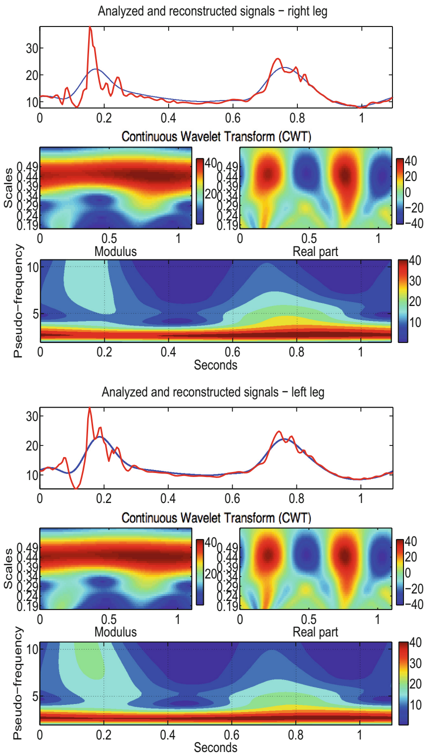

Fig. 4. The analyzed signal and reconstructed signal after inverse wavelets transform of a person right (a) and left (b) leg. Continuous wavelet transform of the analyzed signal obtained by using Morlet wavelet of parameter 4, where modulus, real part and modulus vs. pseudo-frequencies of wavelet coefficients are shown in case of normal gait.

is moved on other leg, what allows person step forward. In the Fig. 2. it is characterized by relatively large knee angle changes. It is seen in the figures, in the case of normal gait, that the pace is nearly harmonic. The main part of energy, which a man need to move, is relatively evenly distributed during the step and change harmonically during this step. The symmetry of the steps is also evident in these figures. Additionally, lower figures show the same wavelet transform as the figure presents absolute values (modulus) of wavelet coefficients but after recalculation to pseudo-frequencies. For comparison, in the Fig. 5 there is presented the case of abnormal gait obtained from a person with disease recorded and reported in the form of spine magnetic resonance, shown in Fig. 3. In real this disease appears as a human left leg limping. In the Fig. 5 there are recorded signal and analyzed by using the same wavelets with the same parameters as in case of normal gait. Comparing the analysis in both figures (Figs. 4 and 5) it is possible to observe the asymmetry of a gait in Fig. 5. In this case the significant

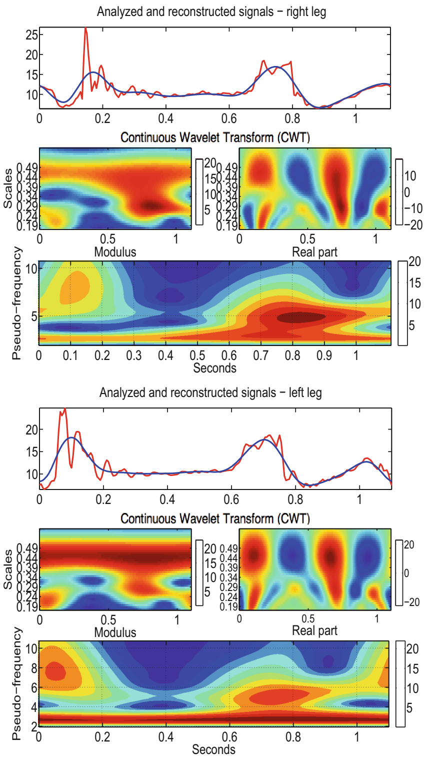

Fig. 5. The analyzed signal and reconstructed signal after inverse wavelets transform of a person right (a) and left (b) leg. Continuous wavelet transform of the analyzed signal obtained by using Morlet wavelet of parameter 4, where modulus, real part and modulus versus pseudo-frequencies of wavelet coefficients are shown below in case of abnormal gait.

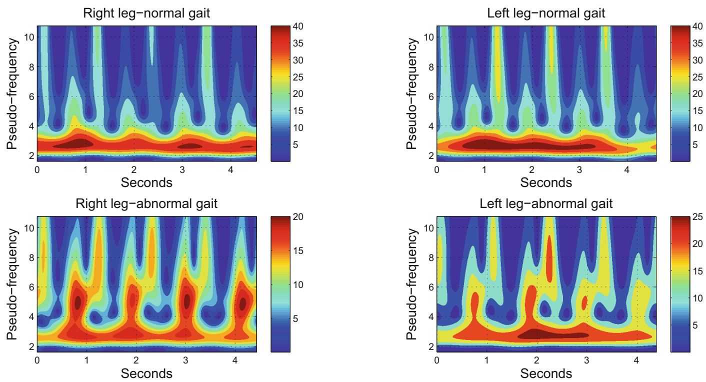

Fig. 6. Continuous wavelet transform of the analyzed signal obtained by using Morlet wavelet of parameter 4, modulus versus pseudo-frequencies of wavelet coefficients are shown in case of normal and abnormal gait for several step.

differences occur in scales low value range. In comparison to Fig. 4 i.e. the normal gait, the abnormality occurs in Fig. 5 as the areas in time range from 0 s to 0.2 s and from 0.6 s to 0.9 s in both legs. In the first time's range the sum of acceleration components and in the same way force characterized by pseudo-frequency between 6–10 Hz and in the second time range by pseudo-frequency between 4–6 Hz represents this abnormality. The next difference is clearly seen in values of wavelets coefficients in harmonic band of normal and abnormal gait signal. The normal gait is nearly harmonic and main amount of force is imposed on that period. In the case of normal gait the values of wavelet coefficients in harmonic band for both legs equal 40, while in the case of abnormal gait equal approximately 15 for right leg and 25 for left leg. It seems that some part of energy is "wasted" on unwanted movement. That mention above is confirmed in case of several steps analyzed in sequence shown in Fig. 6. It is still seen fro that analysis that normal gait is harmonic, which is the effect opposite to abnormal gait. In each step in case of person with disease is the additional force or move component in higher frequency than harmonic component.

5 Discussion

We presented the design of a portable wireless sensor network that can be used for real-time monitoring of lower-limb kinematics during gait. Due to the importance of the joint kinematics to assess the gait technique, we focus on measuring the knee joint angle. We performed experiments with a health and person and with patient with a lumbar disc. Firstly, the MR was performed and after diagnosis the experiment was done. The solution proposed is not constrained to obtain lower limb angles only. It can be used for analyzing human abnormal locomotion. In this work the wavelet transform is applied for chosen signal represented by acceleration. On the one hand it gives a information about the force introduce during the gait and other hand the wavelet transformation of this signal gives a energy concentration during the gait and possibility to focus on chosen part of signal simultaneously in time and frequency domain. These feature may be a useful tool to compare the specific details and differences in human gait. Next the analysis give the possibility to recognize a specific feature of abnormality in human gait caused by specific diseases. The many more analysis are possible using wavelets. In the paper we propose the methodology, which helps to recognize specific feature of human gait, that can be useful in health diagnostic or sport individual training programs creation.

References

1. Bamberg, S.J.M., Benbasat, A.Y., Scarborough, D.M., Krebs, D.E., Paradiso, J.A.: Gait analysis using a shoe-integrated wireless sensor system. IEEE Trans. Inf. Technol. Biomed. **12**, 413–423 (2008)
2. Chen, X.: Human Motion Analysis with Wearable Inertial Sensors. University of Tennessee, Doctoral Dissertation, Knoxville (2013)

3. Daubechies, I.: Ten Lectures on Wavelets Philadelphia. Society for Industrial and Applied Mathematics (SIAM), Philadelphia (1992)
4. Farage, M.: Wavelet transforms and their application to turbulence. Ann. Rev. Fluid. Mech. **24**, 395–457 (1992)
5. Glowinski, S., Krzyzynski, T.: An inverse kinematic algorithm for human leg. J. Theor. Appl. Mech. **54**(1), 53–61 (2016)
6. Glowinski, S., Krzyzynski, T., Pecolt, S., Maciejewski, I.: Design of motion trajectory of an arm exoskeleton. Arch. Appl. Mech. **85**, 75–87 (2015)
7. Liu, T., Inoue, Y., Shibata, K., Shiojima, K., Han, M.M.: Triaxial joint moment estimation using a wearable three-dimensional gait analysis system. Measurement **47**, 125–129 (2014)
8. Mallat, S.: A Wavelet Tour of Signal Processing. Academic Press, San Diego, CA (1998)
9. Sun, W.: Convergence of Morlet's Reconstruction Formula. Preprint (2010)
10. Tadano, S., Takeda, R., Miyagawa, H.: Three dimensional gait analysis using wearable acceleration and gyro sensors based on quaternion calculations. Sensors **13**, 9321–9343 (2013)
11. Torrence, C., Compo, G.P.: A practical guide to wavelet analysis. Bull. Am. Meteorol. Soc. **79**, 61–78 (1998)
12. Zhu, R., Zhou, Z.A.: A real-time articulated human motion tracking using tri-axis inertial/magnetic sensors package. IEEE Trans. Neural Syst. Rehabil. Eng. **12**, 295–302 (2004)
13. ProMove wireless inertial sensing platform. http://www.inertia-technology.com/promovemini