Computational method for analysis and filtering of the CG motion signals during gait based on the Fourier series analysis.

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Abstract— **The motion of the human Center of Gravity (CG) is the result of all the external forces applied onto the body during gait. The motion of the CG can be an important descriptive of pathological gait and has been used to evaluate gait efficiency and symmetry, often with a calculation of external work involved in it[1]. The CG motion in the saggital plane during normal gait is closely sinusoidal, with a period of half the gait cycle and an amplitude of about 4 to 5 cm [2,3]. The frequency content of the CG motion signal ranges between 0.5 Hz to 8 Hz [2,3]. The aim of this study was to analyse and filter the CG motion signals during gait, based on Fourier Series analysis and to clarify it's characteristics at various parts of gait. The bio-sensor was selected for its sensitivity to acceleration and was calibrated through application of sinusoidal oscillations of known frequency and amplitude. Correlation equations were established between the signal, frequency and amplitude. The signal from walking subjects was analyzed to Fourier Series and displacement, velocity and acceleration were derived by inverse transformations. The signal was also filtered to remove high frequency components, comprising noise. Data acquisition, processing, and presentation was achieved by a compact software, designed for user friendly operation in the clinical environment.**

I. INTRODUCTION

The motion of the human Center of Gravity (CG) is the result of the external forces (body weight and ground reaction force) applied onto the body during gait. The ground reaction force is the combined result of both gravitational force and muscle activity [1,4]. Therefore central nervous system disorders and musculoskeletal disorders influence the motion of the CG of the body [5,6,7]. The vertical component of the CG displacement of the human body has been presented as an excellent tool in analysis of human gait to estimate walking efficiency [8,9,10]. It has also been used by many researchers as a method for estimating energy expenditure [11,12,13] and as a tool to examine the asymmetry of gait between the left and right side [1, 10].

Various methods of estimating the vertical displacement of the CG have been described. Those include:

- applying segmental analysis to derive the body CG positions from the locations and displacements of the CGs of various body segments
- recording the displacement of a marker placed close to the actual body CG using video techniques and assuming that the marker mimics the motion of the CG
- employing force plates to measure ground reaction force and estimate CG displacement by double integration of acceleration data.

The first of the above mentioned techniques, requires assumptions on the exact location of the CG of each segment, along with the employment of many markers. Both are introducing error, on the one hand, and make the test cumbersome for the patient, on the other. Furthermore, all the above techniques require costly equipment and trained personnel. This makes them suitable mostly for research laboratories rather than for clinical environments.

The aim of this study is to analyse and filter the CG motion signals during gait in the clinical environment. The technique is based on Fourier Series analysis, using a sensor selected for its sensitivity to acceleration and provides the vertical acceleration, velocity and displacement of the CG of the body. According to the literature, accelerometers have been used mostly to estimate the CG accelerations during gait and not for the determination of the displacements and velocities [16-19].

II. MATERIALS AND METHODS

A. Sensor and calibration

It is known that the CG motion in the saggital plane during normal gait is closely sinusoidal, with a period of half the gait cycle and an amplitude of about 4 to 5 cm [2,3,9,14]. The frequency content of the CG motion signal ranges between 0.5 Hz to 8 Hz [2,3,9,14]. We chose a sensor, sensitive to acceleration, to investigate the CG motion in the saggital plane. We calibrated the sensor at different oscillations of known frequency ranging between 0.5 Hz and 10 Hz. For each oscillation frequency we calibrated the sensor at amplitudes ranging between 5 mm and 10 cm. The equations correlating the sensor signal with the oscillation amplitudes for each oscillation frequency are linear (Fig 1).

That is :

$$d = b_d \times s \qquad (1)$$

where d is the displacement and s is the sensor signal.

Similarly

$$u = \beta_u \times s \qquad (2)$$

and

$$a = \beta_a \times s \qquad (3)$$

where u is the velocity and a the acceleration.

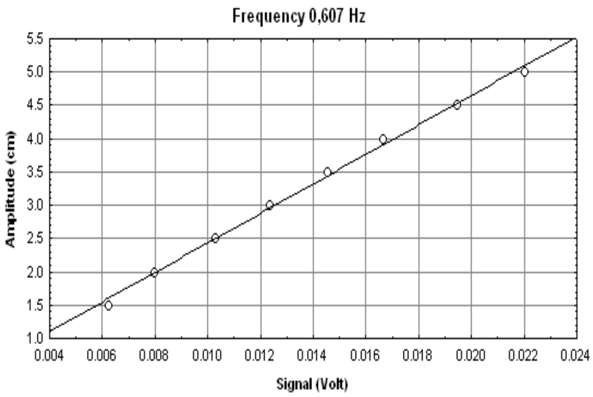

Fig. 1 Sensor signal for different oscillation amplitudes for a given oscillation frequency.

The inclination b_d is a function of the reciprocal of the frequency of oscillation and it is shown in Fig. 2.

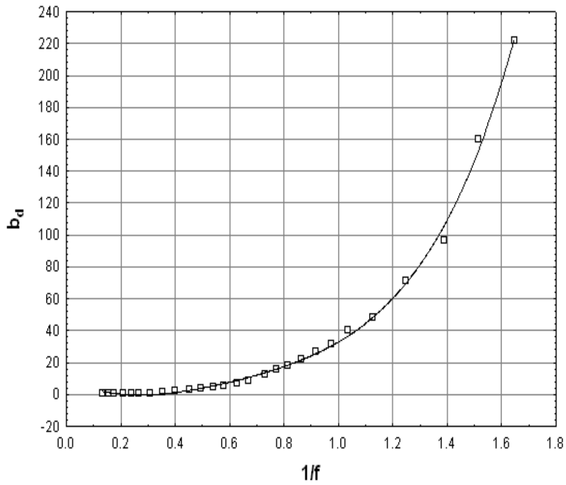

Fig. 2. Correlation equation between displacement coefficients (b_d) and 1/f (f = frequency).

Similarly Figs. 3 and 4 show b_u and b_a as a faction of the of the reciprocal of the frequency respectively.

Displacement, velocity and acceleration can be calculated from the sensor signal and the corresponding values of b_d, b_u and b_a at different frequencies (f).

B. Fourier Series Analysis on the experimental data

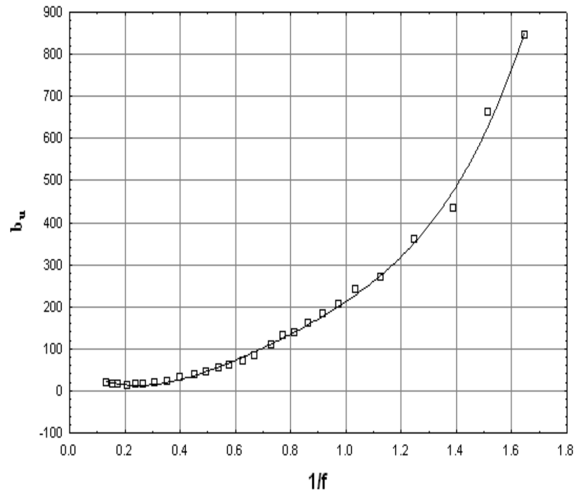

Fig. 3. Correlation equation between velocity coefficients (b_u) and 1/f (f = frequency).

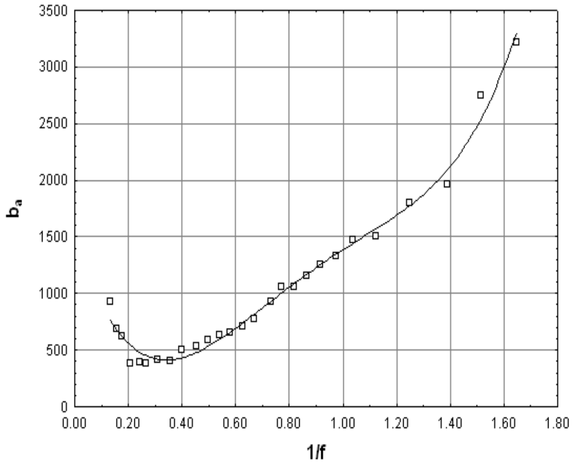

Fig. 4. Correlation equation between acceleration coefficients and 1/f (f = frequency).

Fourier Series analysis can be applied to represent a series of discrete data as a series of sinusoidal terms (harmonics) [20,21].

The sensor signal is sampled at equal time intervals, using an A/D converter and resulting in a series of discrete data x(i), i $\in$ {0,1,2,3…..,2N} spanning over a multiple of the gait cycle. Assuming that our data describe a waveform with period of T = (2N+1)×dt then a trigonometric sum which collocates with the data function at 2N+1 prescribed arguments is as below:

$$x(i) = \frac{1}{2}a_0 + \sum_{j=1}^{N} a_j \times cos(2\pi \times f_j \times i) \times dt + \sum_{j=1}^{N} b_j \times sin(2\pi \times f_j \times i) \times dt \qquad (4)$$

where

$$f_j = \frac{1}{(2N+1)\times dt}\times j \tag{5}$$

and a_j, b_j are the Fourier coefficients.

$$a_j = \frac{2}{T}\sum_{i=1}^{2N} x(i)\times cos(2\pi\times f_j\times i)\times dt \tag{6}$$

$$b_j = \frac{2}{T}\sum_{i=1}^{2N} x(i)\times sin(2\pi\times f_j\times i)\times dt \tag{7}$$

C. *Filtering*

Fourier Series has been used from many researchers as a filtering method for biomechanical discrete data [22-26]. We assumed that pathological gait signal frequency content span between 0.5 Hz and 10 Hz. We therefore, dropped Fourier Series terms corresponding to harmonics of frequency greater than 10 Hz, as they are considered noise. Thus equation 4 can be transformed to:

$$X(i) = \frac{1}{2}a_0 + \sum_{j=1}^{L} a_j \times cos(2\pi\times f_j\times i)\times dt + \sum_{j=1}^{L} b_j \times sin(2\pi\times f_j\times i)\times dt \tag{8}$$

where

$$L \le 10\times(2N+1)\times dt$$

D. *Calculation of displacement, velocity and acceleration.*

Each harmonic in equation 8 is of a known frequency f_j. Therefore b_d can be derived, according to Fig. 2 and the corresponding term of displacement d_j is calculated from equation 1. Finally displacement is:

$$d = \sum_{j=1}^{L} d_j$$

Similarly, velocity and acceleration were calculated. Typical graphs of sensor signal, displacement, velocity and acceleration are shown in Fig. 5.

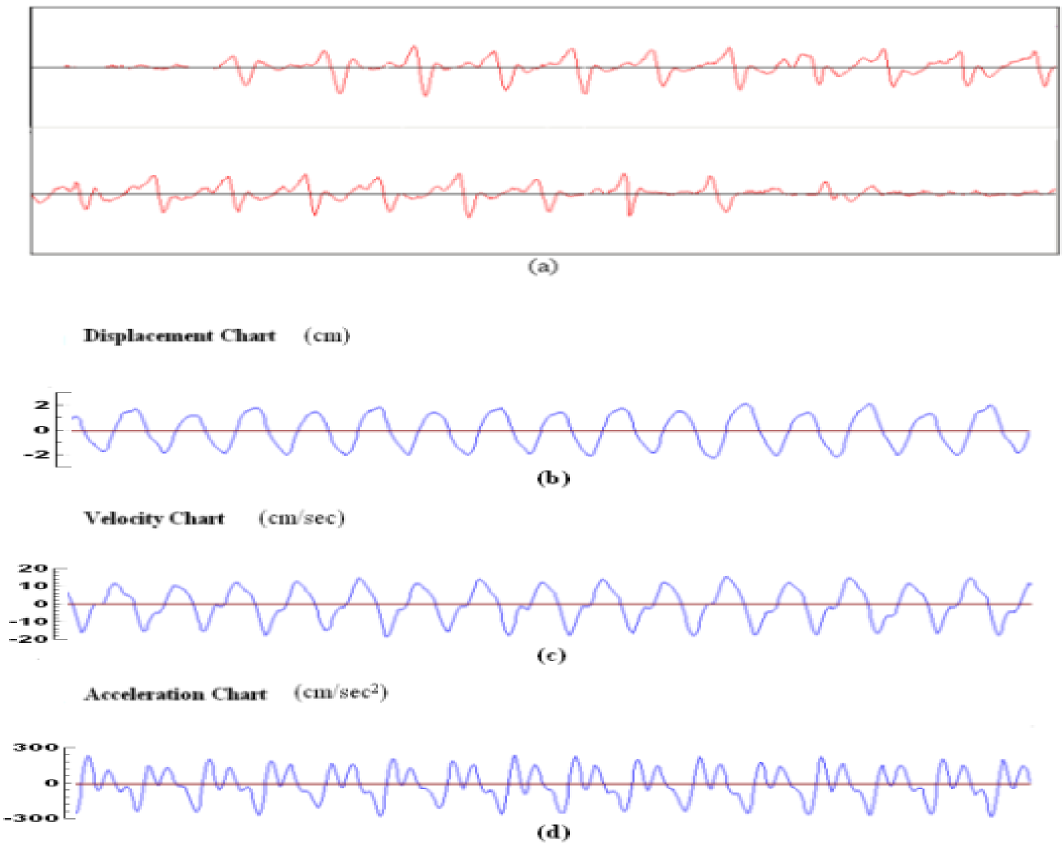

Fig. 5 (a) The raw sensor signal (in mvolts) for a normal walker as it shows on the pc monitor. (b) The displacement (in cm), (c) velocity (in cm/sec) and (d) acceleration (in cm/sec^2) charts for the same walker as they are shown on the pc monitor after the transformations and the filtering.

E. Accuracy of the method.

The accuracy of the method was tested using a system of video cameras in parallel with our sensor. Displacement was calculated at five frequencies (f_1 = 1 Hz, f_2 = 2.5 Hz, f_3 = 5 Hz, f_4 = 6.5 Hz and f_5 = 8 Hz) and five to eight different oscillation amplitudes at each frequency. Our method resulted to amplitudes differing from those calculated by the video system by an average of 1.88 mm (SD = ± 0.46 mm). Displacement estimation by our method as compared to that by the video technique is shown in Fig. 6.

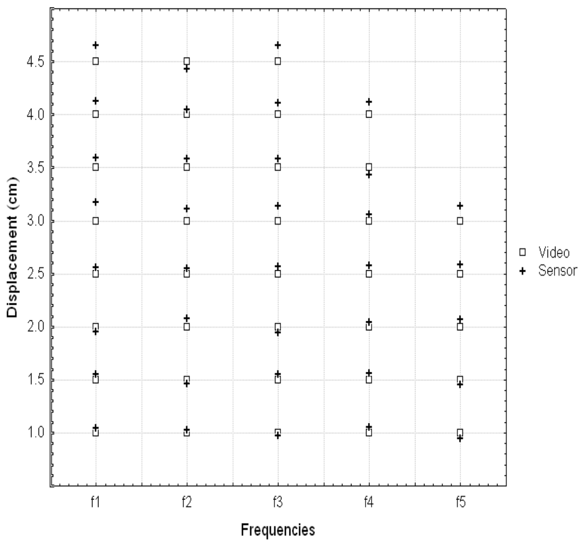

Fig. 6 Video and sensor estimations of displacement for five different random frequencies

III. DISCUSSION

The method, presented in this study, can be applied to obtain the position, velocity and acceleration of the body CG during human gait. It has been applied on human gait data obtained by a sensor, sensitive to acceleration, positioned at the pelvis, close to the actual body CG.

The whole system is low cost, requires minimal user training and can be used in the clinical environment. It was tested against a video camera system and it was proved to be sufficiently accurate. Furthermore, in contrast with video camera or force plates systems, our system preserves the advantage of providing kinematical data of the body CG over multiple gait cycles.

REFERENCES

[1] L. Tesio, D. Lanzi and C. Detrembleur "Motion of the center of gravity of the body in clinical evaluation of gait", Am. J. Phys. Med., vol. 64(2), pp. 75-70, 1998.

[2] Antonsson K. E., Mann W. R. The frequency content of gait. J Biomech. vol 18, No 1, pp. 39-47, 1985.

[3] W.H., Gage, D.A., Winter, J.S., Frank and A.L., Adkin "Kinematic and kinetic validity of the inverted pendulum model in quiet standing", Gait and Posture, vol. 19(2), pp. 124-132, 2004.

[4] Murray M P, Seireg A, Scholz R C. Center of gravity, center of pressure, and supportive forces during human activities. J Appl Physiol 23, pp. 831-838, 1967.

[5] Dieric F, Domicent C, Detrembleur C. Relationship between antagonistic leg muscles co-ordinations and human centre of gravity mechanics in different level gait disorders. J Electromyogr Kinesiol, vol. 12, pp. 59-66, 2002.

[6] Detrembleur C, van den HA, Dierick F. Motion of the body centre of gravity as a summary indicator of the mechanics of human pathological gait. Gait Posture, vol. 12, pp. 243-50, 2000.

[7] Gutierrez M A, Bartonek Å, Haglund-Åkerlind Y, Saraste H. Centre of mass motion during gait in persons with myelomeningocele. Gait & Posture, vol. 18, pp. 37-46, 2003.

[8] Shimba T. An estimation of center of gravity from force platform data. J Biomech, vol. 17, pp. 53-60, 1984.

[9] Saunders J B D, Inman V T, Eberhard H D. The major determinants in normal and pathological gait. J Bone Jt Surg, 35A, pp. 543-558, 1953.

[10] Iida H, Yamamuro T. Kinetic analysis of the human body in normal and pathological gaits. J Biomech., vol. 20, pp. 987-995, 1987.

[11] Martin P E, Morgan D W. Biomechanical considarations for economical walking and running. Med Sci Sport Exerc, vol. 24, pp. 467-474, 1992.

[12] Cotes J E, Meade F. The energy expenditure and mechanical energy demand in normal walking. Ergonomics, vol. 3, pp. 97-119, 1960.

[13] Cavagna G A. Force platforms as ergometers. J Appl Physiol vol. 39, pp. 174-179, 1985.

[14] Johnson R E. A technique for determining the path of the whole body center of gravity. Res Q, vol. 48, pp. 222-232, 1977.

[15] Thirunarayan A M, Kerrigan C, Rabuffetti M, Della Croce U, Saini M. Comparison of three methods for estimating vertical displacement of center of mass during level walking in patiens. Gait & Posture, vol. 4, pp. 306-314, 1996.

[16] Masaki, S. Toshino, T. Tatsuo, T. and Yasuhiro, F. Classification of waist-acceleration signals in a continuous walking period. Medical Engineering & Physics, vol. 22, pp. 285-291, 2000.

[17] Smidt, G.L., Arora, J.S., Johnston, R.C. Accelerographic analysis of several types of walking. Am J Phys Med., vol. 50, pp. 285-300, 1971.

[18] Morris, J.R.W. Accelerometry – A technique for the measurement of human body movements. J. Biomechanics, 6, pp. 729–736, 1973

[19] Currie, G., Rafferty, D., Duncan, G., Bell, F., Evans, A.L. Measurement of gait by accelerometer and walkway: a comparison study. Med Biol Eng Comput., vol. 30, pp. 669-70, 1992.

[20] Manley, R. G., Waveform Analysis, pp. 143-144, Chapman and Hall, London, 1945.

[21] Jacobs A. N., Skorecki J., Analysis of the vertical component of force in normal and pathological gait. J. Biomech. Vol. 5, pp. 11-34, 1972.

[22] Damico M., Ferrigno G., Comparison between the more recent techniques for smoothing and derivative assessment in biomechanics. Med. and Biol. Eng. and Comp., 30, pp. 193-204, 1992.

[23] Hatze H., The use of optimally regularized Fourier series for estimating higher-order derivatives of noisy biomechanical data. J. Biomech., 14, pp.13-18 1981.

[24] Giakas G. Baltzopoylos V., A comparison of automating filtering techniques applied to biomechanical walking data. J. Biomech., 30, pp.847-850 1997.

[25] Woltring H. J., On optimal smoothing and derivative estimation from noisy displacement data in biomechanics. Hum. Mov. Science, 4, pp. 229-245, 1985.

[26] Alexander R. M. and Jays A. S. Fourier analysis of forces exerted in walking and running. J. Biomech., 13, pp. 383-390, 1980.