Biomedical Signal Processing and Control 18 (2015) 56–60

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

journal homepage: www.elsevier.com/locate/bspc

Characterizing gait asymmetry via frequency sub-band components of the ground reaction force

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ARTICLE INFO

Article history:
Received 9 February 2014
Received in revised form
25 September 2014
Accepted 10 November 2014

Keywords:
Gait analysis
Gait asymmetry
Wavelet transform
Ground reaction force

ABSTRACT

This study introduces gait asymmetry measures by comparing the ground reaction force (GRF) features of the left and right limbs. The proposed features were obtained by decomposing the GRF into components of different frequency sub-bands via the wavelet transform. The correlation coefficients between the right and left limb GRF components of the same frequency sub-band were used to characterize the degree of bilateral symmetry. The asymmetry measures were then obtained by subtracting these coefficients from one. To demonstrate the effectiveness of these asymmetry measures, the proposed measures were applied to differentiate the walking patterns of Parkinson's patients and healthy subjects. The results of the statistical analyses found that the patient group has a higher degree of gait asymmetry. By comparing these results with those obtained by conventional asymmetry measures, it was found that the proposed approach can more effectively distinguish the differences between the tested Parkinson's disease patients and the healthy control subjects.

1. Introduction

As an indispensable element of daily activity, gait is a complex motor skill governed by several inter-linked pathways. A possible approach that can help us understand the mechanism behind limb coordination in generating the gait motion is to study gait asymmetry (GA). Despite the fact that the symmetry of normal walking remains a controversial issue [1,2], many studies have demonstrated that marked GA appears in many pathological conditions. For example, studies have found that limb length discrepancy [3], stroke [4], cerebral palsy [5] and Parkinson's disease (PD) [6] may result in a significantly asymmetrical gait because bilateral differences in the support time, stride length, ground reaction force (GRF), muscle moments or joint motion have been detected for these patients.

The asymmetrical gait features that have been studied can be divided into two categories: (1) discrete parameters, such as swing time [7] and stride length [8], and (2) continuous signals, such as joint displacement [9], GRF [10] and electromyography [11] signals. Compared with the discrete parameters, a distinct advantage of the continuous signals is that they can be analyzed by both time and frequency domain methods. As a result, one can often extract more information from these gait signals to study GA.

In comparison with other continuous gait signals, a distinct property of the GRF is that the acceleration of the center of mass (COM) of the body is directly proportional to GRF. As a result, many features can be extracted from GRF to differentiate healthy and abnormal gait patterns. For example, the diagnostic potentials of GRF for pathological gaits have been demonstrated for ankle arthrodesis [12], hip arthroplasty [13], patellofemoral pain syndrome [14], multiple sclerosis [15] and peripheral arterial disease [16], etc. However, little attention has been given to the development of GRF-based asymmetry measures to detect gait abnormalities.

Parkinson's disease (PD) is one of the most common age-related neurodegenerative disorders and is expected to impose an increasing burden as society ages [17,18]. Initializing early therapy by early diagnosis is considered to be very important for the management of PD [19]. It is also believed that early diagnosis of PD can pave the way for major advances in disease-modifying therapies [20]. Unfortunately, the diagnosis of PD still remains mainly clinical and is very difficult in the early stages of the disease [21]. Hence, many

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http://dx.doi.org/10.1016/j.bspc.2014.11.008
1746-8094/

physiological signal based computer-aided-diagnosis (CAD) methods have been proposed to help physicians to make better diagnostic decisions. Since most important symptoms of PD include muscle rigidity, tremors and changes in speech and gait, these CAD methods often extract features from muscle activity [22–24], acoustic signal [25–27] or gait motion [28–30] to discriminate patients with PD. Among these CAD methods, gait based techniques are uniquely challenging and valuable for several reasons. First, early gait dysfunction can be subtle and non-specific and is often erroneously ascribed to old age or medical conditions such as osteoarthritis. This is very likely the reason why PD patients presenting with gait disturbance experienced the longest diagnostic delay [31]. Second, gait difficulty has been shown to be a predictor of decreased survival in PD [32]. Therefore, by characterizing the severity of gait dysfunction with quantified measures, these CAD methods have the potential to improve the treatment of PD by monitoring the progression of gait disorder.

Quantitative gait differences between normal subjects and PD patients have been discussed since 1980s [33,34]. In 1990s, several studies have investigated the stride length and stride time differences between PD and normal subjects [35–39]. Due to the disruption of neuromuscular control of gait, PD is characterized by asymmetric motor deficits in both the upper and lower extremities [40]. Consequently, later studies have tried to compare the degree of GA between PD patients and healthy subjects. For example, it has been shown that PD patients have larger asymmetry in swing time [6,7] and arm swing magnitude [41] than healthy individuals. Since gait analysis can produce a large number of features to characterize abnormal gait patterns, recent studies have tried to develop PD diagnostic methods by combining multiple number of gait features such as walking speed, peak flexion of the knee joint and ankle displacement [42–45]. However, most of these approaches focus on the kinematic parameters of the gait. Relatively few studies have tried to use the kinetic features such as GRF to diagnose PD patients [46,47].

The aim of this work is to introduce GA measures by performing time-frequency spectral analysis on the GRF signals via the wavelet transform. It is hypothesized that the degree of asymmetry of the wavelet-decomposed GRF signal components of the pathological gaits is larger than that of the normal gaits. The validity of this hypothesis will be tested by comparing the proposed GA measures between the PD patients and the healthy control subjects.

The gait dataset studied in this work is obtained from Physionet [48]. The vertical component of the GRF (VGRF) was measured as the test subjects walked at their usual, self-selected pace for approximately 2 min. The sampling rate was chosen as 100 Hz. The original form of the data included eight VGRF components measured by eight sensors located at different spots under the foot. The VGRF was obtained by totaling the outputs of these eight sensors and then dividing by the weight of the tested subject. The original dataset consists of 93 PD patients (58 males and 35 females) and 73 healthy subjects (40 males and 33 females). However, two male and two female PD patients and one healthy male subject were not included in this study because of the lack of weight data.

2. Methods

2.1. Measurements

This study focuses on VGRF which is the force component with the largest magnitude that the ground impacts on the body. Fig. 1 shows a typical M-shape VGRF profile of a normal walking gait [49]. Three characteristic points can be identified from such a VGRF profile. As shown in Fig. 1, this standard walking VGRF profile exhibits two peaks. The first peak (F_1) corresponds to the period right after the heel strike when the center of gravity is moving downward, resulting in an increased VGRF. The second peak (F_2) occurs when the person applies a force to the ground which is then matched by an increase in the VGRF. The dip (F_d) that comes between these two peaks occurs when the COM is rising up, thus decreasing the force of the body on the ground and resulting in the reduction of the VGRF. As shown in Fig. 1, the times of occurrence of F_1, F_2 and F_d are denoted as T_1, T_2 and T_d, respectively, and T is the time length of the step. In addition, every VGRF signal used in this study was normalized by dividing the outputs of the GRF sensors with the weight of the tested subject.

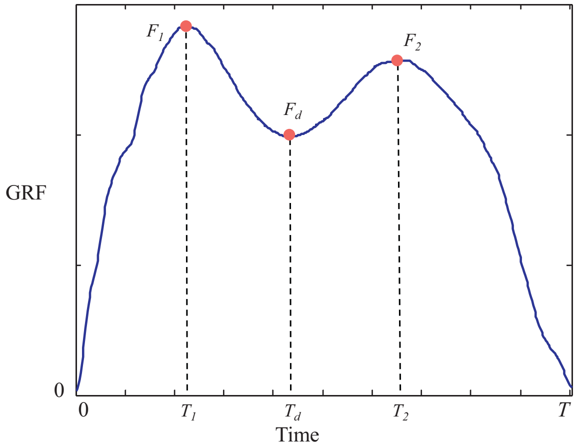

Fig. 1. A typical walking GRF profile.

Because the swing and stance phases of a gait cycle can be detected by inspecting the magnitude of the GRF signal, one can easily determine step time, stance time, swing time and double stance time from the measurements of the GRF. The capability of deriving these important temporal gait features is also an advantage of GRF measurements.

Typically, gait asymmetry measures are developed by comparing the gait features of the left and right limbs. For the discrete parameter features, one of the most commonly employed GA measures is

$$GA = \frac{|X_L - X_R|}{2|X_L + X_R|}$$

where X_R and X_L are the values of the discrete parameter feature measured from the right and left limbs, respectively. The discrete parameter features studied in this work include the temporal features stance time, swing time, double stance time and the dynamic features $F_1, F_2, F_d, F_1/T_1$ (loading rate) and $F_3/(T - T_2)$ (push-off rate). Note that all these features can be derived from the GRF.

In addition to the discrete parameters, this study also performs a bilateral comparison for the VGRF signals. To achieve this goal, a VGRF signal was decomposed into a number of sub-band components via the wavelet transform. Compared with the traditional Fourier-based methods, which directly decomposes a signal into an infinite number of sinusoidal components of different frequencies, the wavelet transform has the following distinct advantages. First, wavelet methods can systematically decompose a complicated signal into a finite number of frequency sub-band components, which can be independently studied. Second, by using basis functions localized in time and frequency, the wavelet transform provides a systematic framework for analyzing the non-stationary signals. Third, the wavelet transform uses a window with a variable time size to process the signal. As a result, a good frequency resolution at low frequencies and a good time resolution at high frequencies can be simultaneously achieved. In contrast, the traditional Fourier