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Inertial sensing algorithms for long-term foot angle monitoring for assessment of idiopathic toe-walking

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ABSTRACT

When children walk on their toes for no known reason, the condition is called Idiopathic Toe Walking (ITW). Assessing the true severity of ITW can be difficult because children can alter their gait while under observation in clinic. The ability to monitor the foot angle during daily life outside of clinic may improve the assessment of ITW. A foot-worn, battery-powered inertial sensing device has been designed to monitor patients' foot angle during daily activities. The monitor includes a 3-axis accelerometer, 2-axis gyroscope, and a low-power microcontroller. The device is necessarily small, with limited battery capacity and processing power. Therefore a high-accuracy but low-complexity inertial sensing algorithm is needed. This paper compares several low-complexity algorithms' aptitude for foot-angle measurement: accelerometer-only measurement, finite impulse response (FIR) and infinite impulse response (IIR) complementary filtering, and a new dynamic predict-correct style algorithm developed using fuzzy c-means clustering. A total of 11 subjects each walked 20 m with the inertial sensing device fixed to one foot; 10 m with normal gait and 10 m simulating toe walking. A cross-validation scheme was used to obtain a low-bias estimate of each algorithm's angle measurement accuracy. The new predict-correct algorithm achieved the lowest angle measurement error: $<5^\circ$ mean error during normal and toe walking. The IIR complementary filtering algorithm achieved almost-as good accuracy with less computational complexity. These two algorithms seem to have good aptitude for the foot-angle measurement problem, and would be good candidates for use in a long-term monitoring device for toe-walking assessment.

1. Introduction

"Toe walking" is the condition of weight bearing preferentially through the forefoot as compared to normal heel-toe gait. It is common in young children learning to walk, who usually develop a normal gait pattern by 3.5–4 years of age [1]. When otherwise normal children exceeding this age still exhibit toe walking, the condition is termed "Idiopathic Toe Walking" (ITW). Prolonged ITW can lead to complications including shortened Achilles tendons, structural abnormalities, and balance impairment. Treatments for ITW include serial casting to improve dorsiflexion [2], Botox injections [3], or surgical lengthening of the Achilles tendon [4].

Treatment choices depend on the severity of the condition, which can be categorized using a system proposed by Alvarez et al. [5]. This system uses gait analysis metrics obtained using motion capture to differentiate between "mild", "moderate", and "severe" ITW. Unfortunately, severity assessments made in a gait lab may be inaccurate because some ITW children are able to control their gait temporarily, especially during observation by clinicians. Thus it is suspected that ITW may sometimes be underdiagnosed, and its severity underappreciated.

A tool to assess the severity of ITW *outside* the clinic would be useful. This tool could be realized by using inertial sensors (accelerometers and gyroscopes) to monitor an ITW child's foot angle during daily activity. The long-term foot angle measurements would reflect gait abnormalities and allow more accurate ITW assessment. Ideally the tool would provide feedback to train

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the children to walk normally, which may improve quality of life for mild to moderate ITW children. Therefore the conceived foot-monitoring device includes the sensors and a small microprocessor which computes foot angle in real-time, and provides real-time feedback as necessary.

Micro-electromechanical (MEMS) inertial sensors have become commonplace in biomechanical analysis [6–9] largely because they are small and inexpensive. Tri-axial accelerometers measure acceleration in three axes, making them good tilt sensors in static cases – where gravity is the only acceleration. However in dynamic conditions, external accelerations are inseparable from gravity and the tilt measurement becomes inaccurate. Gyroscopes measure angular velocity about a single axis. Orientation in planar motion can be found by integrating angular velocity, while for 3D orientation a tri-axial gyroscope is used with a rotation matrix. This works well for brief measurement periods, but errors are integrated over time and cause drift in gyroscope-based measurements. These sources of error complicate signal processing.

The proposed application of a foot-angle monitor introduces constraints on the signal processing method. In order to provide real-time feedback to the ITW child, the monitor must perform all signal processing in real-time. For prolonged use outside the clinic, the monitor must be small and battery-powered. Thus it will have limited computational power, and signal processing workload must be minimized to preserve battery life.

Literature shows a variety of methods for processing inertial sensor data. Some researchers perform very little processing, simply recording accelerations and integrated angular velocities during biomechanical analysis [10]. Others have used these measurements to identify abnormal gait patterns [11–13] or specific activities [14–18]. As for actual angle measurement, perhaps the most popular approach is Kalman filtering [19,20] which blends accelerometer and gyroscope data. While quite accurate, a well-designed Kalman filter can be computationally complex [21] and therefore ill-suited to our application. The complexity issue arises in other approaches including Weiner filtering [22], fuzzy processing [13], and neural networks [23].

Literature does include some low-complexity algorithms. Some have used accelerometer-only tilt measurement schemes [24] or schemes which rely on the continuous integration of gyroscope signals [25]. While the accelerometer-only approach is apparently valid, the gyroscope drift problem makes gyroscopes inappropriate for prolonged measurement. This drift problem has been addressed by attempting to reset the gyroscope measurement during static conditions or when force sensors under the foot detect a particular gait phase [26]. However both these approaches make assumptions which cannot be guaranteed in this application. A more appropriate approach is complementary filtering [21,27]. Complementary filtering uses filters to extract the most reliable information from each sensor, and then sums the results.

This work evaluates the aptitude of accelerometer-only measurement and complementary filtering for foot angle measurement. A new "predict-correct" algorithm is also proposed, derived using fuzzy c-means clustering to learn an ideal method of blending accelerometer and gyroscope data.

2. Methods

2.1. Data collection

A sensing device including a 3-axis digital accelerometer (ADXL345, Analog Devices, 7.8 mg resolution), and 2-axis analog gyroscope (LPR450, STMicroelectronics, $\pm125^\circ\,\mathrm{s}^{-1}$ range $\approx0.12^\circ\,\mathrm{s}^{-1}$ resolution using 11 bit ADC) was used to collect inertial data from 11 healthy subjects (7 males, 4 females, aged 17–26, mean age 21.5 ± 3.4 years) during gait. The device was mounted on the dorsal part of the shoe (Fig. 1), and sampled inertial sensors at 60 Hz while subjects walked about 10 m in a gait laboratory. At the same time, the true tilt angle of the sensing device was recorded using an eight-camera motion capture system, which tracked two reflective markers placed 5 cm apart on the device. The procedure was performed twice, with subjects walking normally the first time and simulating toe-walking the second. This resulted in 11 normal-walking datasets and 11 toe-walking datasets, each comprising the inertial data and true tilt angle. In a separate test, three additional datasets were collected from two of the subjects – these three sets were used to develop the predict-correct algorithm.

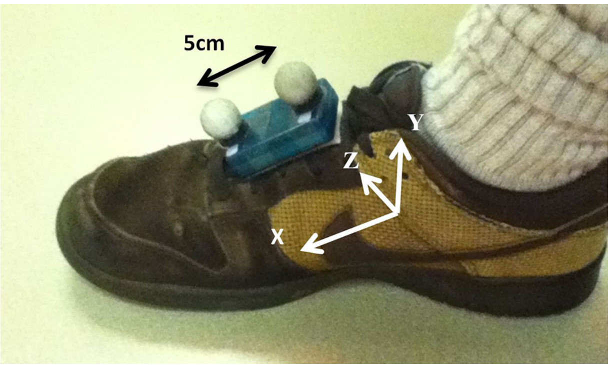

Fig. 1. Placement of the sensing unit on a test subject's foot. A motion capture system tracked the two spherical markers to determine the unit's true tilt angle. The *x*, *y*, and *z* sensing axes of the device are shown.

Throughout this work, 'foot angle' is defined as the angle between gravity and the *z* axis of the inertial sensor (see Fig. 1). The 'sole angle' (the angle between the sole and the ground) can be calculated by subtracting any foot angle offset measured while the patient is standing flat-footed.

2.2. Testing algorithms

Four algorithms were implemented in MATLAB (The MathWorks Inc.) and evaluated on their accuracy in measuring foot angle during gait. Algorithms were evaluated in two situations: normal-walking only (the algorithm was applied to the 11 normal walking datasets, and the average error measured), and mixed walking (the algorithm was applied to all 22 datasets, and the average error measured).

A cross-validation scheme was used to test each algorithm's performance. One dataset was set aside while the algorithm was "trained" (its parameters were tuned) for minimum root-mean-square (RMS) error on the other datasets. The trained algorithm was then applied to the held-out dataset to test its performance. This procedure was repeated – setting aside a different dataset each time – until every dataset had been used as a "test set". The performance across all test sets was averaged and reported. This cross-validation procedure uses all available data for testing, but ensures algorithms are tested on data which was not used for training. Thus it gives a nearly unbiased estimate of algorithms' performance [28].

The complexity of each algorithm was roughly quantified by counting the number of operations involved: Addition, subtraction, multiplication and division were each counted as one operation. Comparisons (used in absolute values and lookup tables) were counted as two.

2.3. Algorithm descriptions

2.3.1. Accelerometry with low-pass filtering

Purely accelerometer-based measurement is perhaps the simplest approach to tilt estimation. Under static conditions