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Assessment of walking, running, and jumping movement features by using the inertial measurement unit

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ABSTRACT

Purpose: To observe various modes of lower limb locomotion, an inertial measurement unit (IMU) was used. Digital signals were used to identify signal characteristics that help to distinguish among locomotion modes and intensity levels.
Methods: A wireless IMU was installed on the outside of shoes and three forms of locomotion (walking, running, and jumping) were assessed at two intensity levels (low and high) to observe the acceleration, foot angular velocity variations, and characteristics of the curve variations in the anteroposterior, mediolateral, and superior–inferior directions.
Results: Most interactions between intensity and locomotion were statistically significant, except for the acceleration in the anteroposterior direction and on the horizontal plane. In addition, as the intensity increased, the values of all the parameters increased. Thus, both the acceleration values and range of angular velocity variation can be used to distinguish the intensity levels. Moreover, the results indicated that the angular velocity in the frontal axis, which is the sequence of the plantar/dorsiflexion movements, can also be used to identify different locomotion.
Conclusions: Uniaxial acceleration or the range of angular velocity variation could be used to identify locomotion intensities, whereas the characteristics of the uniaxial angular velocity curve could be used to identify the locomotion modes.

1. Introduction

Since the development of microelectro mechanical systems, sensors have been frequently applied in exercise science. Recently, the inertial measurement unit (IMU) has been widely applied in health-related research. Because accelerometers are portable and can facilitate extended data collection, they have been applied in physical activity (PA) measurements or used to develop commercial wearable device [1–3]. However, applications under free-living conditions continue to involve limitations, particularly when identifying various movements at different intensity levels.

Studies that have adopted sensors have generally involved energy expenditure estimation and locomotion identification. Studies estimating energy expenditures have typically used the characteristics of the accelerometer signals generated during body movements to investigate the relationship between energy expenditures and PA [4]. Such studies have used preset movements and intensity levels to verify the results of acceleration signals and oxygen intake. In addition, the accelerometer has been adopted to replace metabolic analyzers for measuring energy expenditures and determining the PA amounts by using different thresholds as cut-off points to determine the different levels of PA [5,6]. However, these approaches have required post-processing and complex calculations such as the Fourier transform or wavelet analysis. Most studies on locomotion identification have focused on gait analysis, the discrimination of changes in static postures, and the differentiation of daily life movements [7,8]. Certain studies have observed or monitored a specific target with a specific objective. For example, the angular velocity of foot pronation during running was measured by using gyro sensors to predict lower extremity

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fatigue [9]; other studies have measured the risk of falling among senior citizens, or monitored the number of activities performed by patients with Parkinson's disease [10,11]. However, most research results have been restricted by the aforementioned limitation and thus cannot be used in practice.

Regarding practical application, electronic sensors have replaced mechanical pedometers for calculating PA levels because they are accurate and exhibit functions similar to those of complex physiological instruments [12,13]. However, applying electronic motion sensors to locomotion analysis still involves limitations; currently, such sensors can only partially measure locomotion. Different forms of locomotion may require specific identification approaches [14] and complex signal processing and calculation techniques [15,16]. We believe that each form of locomotion involves movement characteristics and a regular movement sequence. The differences are reflected in the signal characteristics, which can then be used as a basis for locomotion identification. For example, walking and running are similar, but they differ in the double leg support and flight phases [17].

In the future, the application of sensors in exercise science research will involve integrating the advantageous features of portability and extended data collection with locomotion analysis to identify the type of locomotion and intensity level. However, thorough research must be conducted to facilitate selecting a meaningful method of identification when analyzing a substantial amount of data. In addition to walking and running, jumping is a common movement in daily activity and sports, which could affect energy expenditures and PA. Therefore, developing a method that employs sensors to accurately identify major movements (e.g., walking, running, and jumping) and the level of movement intensity would facilitate exercise science research. In this study, various combinations of locomotion and intensity levels (i.e., slow and fast walking, slow and fast running, low and high jumping) were observed using IMU. The signal characteristics of various locomotion and intensity levels were identified and can be used as a reference in future identification.

2. Materials and methods

2.1. Data collection

The participants comprised 15 healthy men (age: 26.9 ± 3.1 years; height: 173.5 ± 5.4 cm; weight: 73.4 ± 9.0 kg) who regularly exercised. Those who had severe lower extremity injuries or cardiovascular diseases were excluded. This study was approved by the human research ethics committee of Taipei Medical University Hospital.

The wireless IMU sensor used in this study comprised a 3-axis accelerometer chip (ADXL345, Analog Devices, MA, USA), 3-axis gyro chip (MPU3050, InvenSense, CA, USA), and ZigBee wireless transmission module. The sampling frequency was set at 200 Hz. The same sensor was used for all participants and was attached to the outside of the left shoe by using double-sided adhesive tape; this facilitated observing the characteristics of various foot movements. In addition, the sensor was securely fixed to the shoe by using athletic tape to prevent noise generation caused by the shifting of the sensor. The sensor measured the acceleration in three orthogonal directions and the angular velocity in three axes, namely the anteroposterior (X), mediolateral (Y), and superior–inferior (Z) axes (Fig. 1). The accelerometer was calibrated by the gravity, and the gyro sensor was calibrated by the Vicon system (Vicon, Oxford, UK). The sampling frequency of the Vicon system was set at 200 Hz. A treadmill (AMG-7310, Magtonic, Tainan, Taiwan) was employed to control the speed of running and walking.

In this study, walking, running, and jumping were observed. Walking and running were examined at two speeds on the treadmill and the participants executed a single jump at two heights from the ground. Walking and running were divided into slow (1.0 m/s) and fast (2.0 m/s) walking and slow (2.0 m/s) and fast running (3.5 m/s). A speed of 2 m/s was used because it is the preferred transition speed (PTS) from walking to running [18]. Normal walking (1.0 m/s) and running (3.5 m/s) speeds were used for slow walking and fast running [19]. The walking and running at those speeds were maintained for 1–2 min to observe the locomotion stability of the participants; after the participants adapted to the speed, 15 s of data were captured. Jumping was assessed at two levels of intensity, namely low (30% of the maximum jumping height) and high jumping (100% of the maximum jumping height). The participants were required to assess their maximum jumping height before the test. To measure the jumping height, a target object was suspended from the ceiling, and the participants jumped while raising their hands. Each type of jump was performed twice, and the jump that reached the required height with stable landing was selected for analysis.

2.2. Data processing and feature evaluation

The collected data were processed using MATLAB R2007b software (The MathWorks, MA, USA). A second-order, 10-Hz

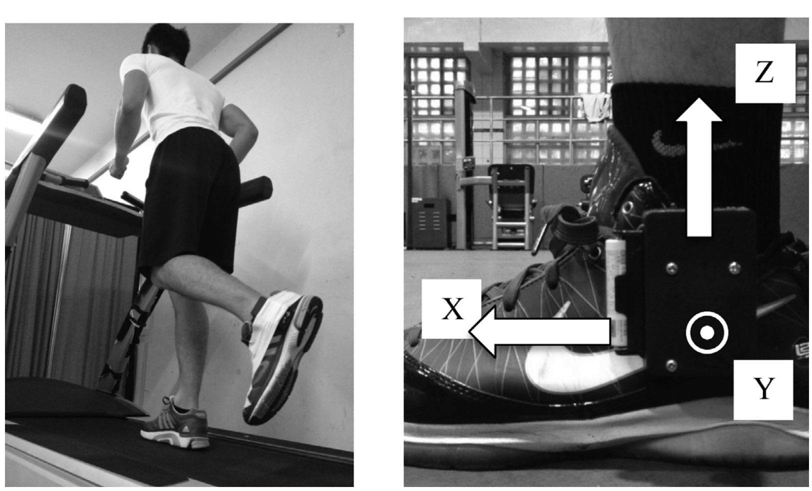

Fig. 1. The setting of IMU module and placement on the subject's left foot (left). Arrows represent anteroposterior (X) axis and superioinferior (Z) axis, dot represent mediolateral (Y) axis (right).