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Development and validation of an accelerometer-based method for quantifying gait events

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Objective: We describe a versatile signal processing algorithm that automatically extracts five consecutive fundamental gait events: heel strike (HS), toe strike (TS), heel-off (HO), toe-off (TO), and heel clearance (HC) from data recorded by an ambulatory accelerometer-based system that uses wireless synchronized accelerometers applied to the left and right feet. We estimate the duration of gait cycle sub-phases computed from these events. We validate these measurements and estimate their temporal accuracy by comparing them to those simultaneously recorded with a force plate, a kinematic 3D analysis system, and a video camera.

Background: Accelerometer-based systems have been proposed as an ambulatory monitoring solution to deal with quantification of gait features. In comparison with conventional gait-analysis laboratory methods, e.g., optoelectronic motion capture systems and instrumented walkways, the accelerometer-based systems are not limited to controlled laboratory environments; they are designed to quantify gait features in an entirely natural setting with the possibility to obtain relevant gait events/parameters over longer walking distances. An important step in the development of such systems is their validation, which is often lacking for most existing systems.

Methods: Seven young and healthy subjects without any previous injury of the lower limbs and with (mean ± standard deviation) age = 27 ± 2.6 years, height = 181 ± 7 cm, weight = 78 ± 9 kg, participated in the gait tests. During these tests, they were asked to walk back and forth on a 12 m long track, at their usual speed.

Acceleration signals during walking were recorded (at 200 Hz) by a wearable, wireless, accelerometer-based hardware system that includes small, synchronized, three-axis accelerometer units, a transmitter module, and a receiver module. For this study, four accelerometer units were attached directly to the subjects' regular shoes at the level of the (left and right) heels and toes.

We developed versatile algorithms to accurately extract relevant gait events from the acceleration signals [1] [3] obtained with this system. The first step of our accelerometer-based method is the gait segmentation based on the continuous wavelet transform (CWT) to identify stride-by-stride gait cycles from foot-mounted accelerometer recordings. This step provides only a rough estimation of these gait cycles; it results in the detection of relevant, local acceleration signals [2]. The second step uses the CWT and a novel piecewise-linear fitting technique to extract, from these local acceleration signals, five fundamental gait events: HS, TS, HO, TO, or HC. We carried out a stride-by-stride validation of gait events timing by comparing the measurements with reference data provided by a force plate, a kinematic 3D analysis system (used as gold standard), and a video camera.

Results: The algorithms were able to correctly extract the above, five gait events in 247 gait cycles for HS and TO, in 230 gait cycles for TS, in 125 gait cycles for HO, and in 839 gait cycles for HC. The temporal accuracy ± precision of the gait events were for HS: 1.3 ms ± 7.2 ms, TS: −4.2 ms ± 10.9 ms, HO: −3.7 ms ± 14.5 ms, TO: −1.8 ms ± 11.8 ms, and HC: 3.2 ms ± 17.9 ms. In addition, the occurrence times of left/right stance, swing, and stride phases duration were estimated with a mean error of –6 ms ± 15 ms, –5 ms ± 17 ms, and –6 ms ± 17 ms, respectively.

Conclusions: The temporal accuracy and precision achieved by the above method for healthy subjects, and the validation results obtained, convince us that the proposed accelerometer-based system and method could be used for assessing pathological gait, e.g., for patients with Parkinson's disease.

References:

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