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Accuracy of three methods in gait event detection during overground running

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ABSTRACT

Inertial measurement units (IMUs) have been extensively used to detect gait events. Various methods have been proposed for detecting initial contact (IC) and toe-off (TO) using IMUs affixed at various anatomical locations. However, the accuracy of such methods has yet to be compared. This study evaluated the accuracy of three common methods used for detecting gait events during jogging and running: (1) S-method, in which IC is identified as the instant of peak foot-resultant acceleration and TO is identified when the acceleration exceeds a threshold of 2*g* in the region of interest; (2) M-method, in which IC and TO are defined as the minimum before the positive peak shank vertical acceleration and the minimum in the region of interest, respectively; and (3) L-method, in which IC is indicated by the instant of peak pelvis anteroposterior acceleration and TO is identified by the maximum in the region of interest. The performance of the IMU-based methods in detecting IC and TO and estimating stance time (ST) were tested on 11 participants at jogging and running speeds against a reference provided by a force-platform method. The S-method was the most accurate for IC detection (overall mean absolute difference (MAD): 4.7 ± 4.1 ms). The M-method was the most accurate for TO detection (overall MAD: 7.0 ± 3.5 ms). A combination of M- and S-methods, called the MS-method, was the most accurate for ST estimation (overall MAD: 9.0 ± 3.9 ms). Thus, the MS-method is recommended for ST estimation; however, this method requires four IMUs for bilateral estimation.

1. Introduction

Initial contact (IC) and toe-off (TO) are two representative events in gait analysis. Accurate identification of these events is critical for determining gait phases precisely, estimating tempo-spatial parameters, and understanding the characteristics of joint movement and patterns of muscle activity in gait-related studies.

IC and TO can be detected using various instruments. Force-platforms and high-speed cameras were commonly used, but they are restrictive in laboratory environments and provide only a limited number of strides per trial. Pressure-sensitive switches (e.g., footswitches) are popular because of their suitability in outdoor environments and long-term recording. However, they are susceptible to mechanical failure and may induce discomfort if worn for long periods [1]. Recently, inertial measurement units (IMUs) have been extensively employed for prolonged outdoor measurements, and various methods referring to IMU locations and detection algorithms have been proposed [2–14]. While many studies used gyroscope-based IMUs [2,12,14], others used accelerometer-based IMUs for detecting IC and TO [3–11]. Either way, researchers would benefit from improved algorithms.

Although IC and TO can be detected using various methods, accuracy is a concern and has been revealed to be associated with the IMU location, because the magnitude and profile of acceleration changed accordingly [1]. The reported differences ranged from 0.42 ms to 147 ms for IC detection during walking [13–16] and from 3.11 ms to 34 ms for TO detection [13,14,16]. The differences for IC detection during walking at natural and slow speeds were 5.7 (± 6.8) and 12.8 (± 7.8) ms, respectively [6]. Only one study reported differences of 66.0 ms and 16.0 ms for IC and TO detection, respectively, during overground running with an IMU placed at ankle level [17]. In the aforementioned studies, an IMU was placed at foot, shank, or waist level and the reference was a force-platform, footswitch, or high-speed camera. However, the accuracy of IC and TO detection was not compared when an IMU was attached to these locations, particularly during running.

Most IMU-based methods were reported using an acceleration profile to detect IC and TO in walking [4–6,9,10,13–16,18,19]. Three methods were commonly found using an IMU to determine IC and TO during running [3,7,8,11,20]. The first method, denoted as L-method, entails using an anteroposterior acceleration profile obtained from an

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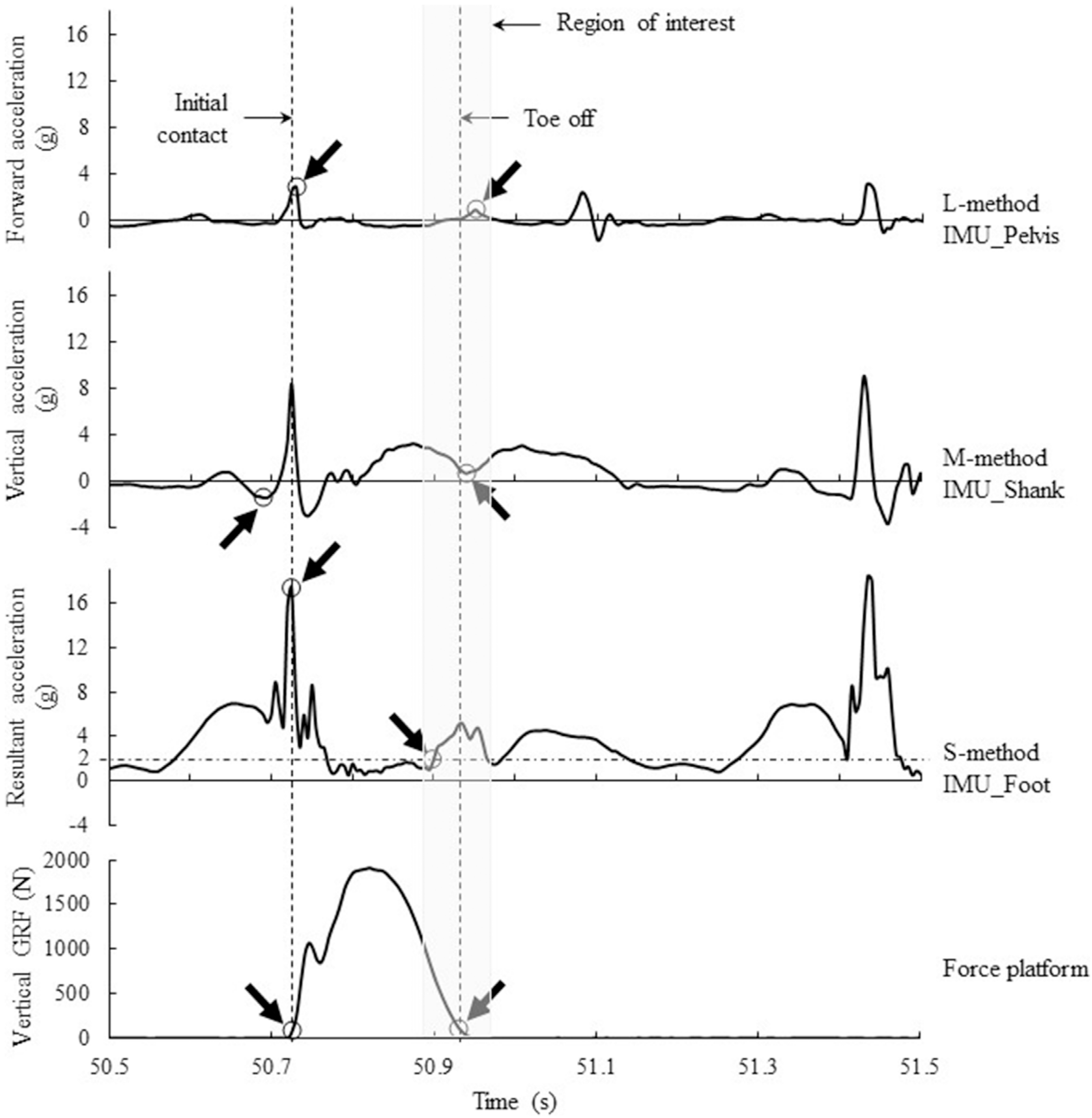

Fig. 1. Various methods for identifying IC and TO. The arrows indicate the points of IC and TO for each method. L-method: IMU was attached to the pelvis; peak forward acceleration point was identified as IC, and the maximum in the region of interest was identified as TO. M-method: IMU was attached to the shank; the minimum before peak vertical acceleration was identified as IC and that in the region of interest was identified as TO. S-method: IMU was attached to the foot; the peak resultant acceleration point was identified as IC and a threshold of 2*g* in the region of interest was identified as TO. Force-platform method: vertical GRF was used; IC was identified when vertical GRF > 10N and TO was identified when vertical GRF < 25N (IMU: inertial measurement unit; g: gravitational acceleration; GRF: ground reaction force).

IMU affixed to the lumbar region; the positive peak indicates IC and the maximum in the region of interest indicates TO (Fig. 1) [3]. This method has an advantage of bilateral IC and TO detection with one IMU. The second method, denoted as M-method, involves analysing the vertical acceleration from an IMU affixed to the tibia. According to this method, the minimum before the positive peak indicates IC and the minimum in the region of interest indicates TO (Fig. 1) [7]. The M-method has been extensively used to investigate shock impact and attenuation during running because the site contains the least soft tissue, which means the IMU could provide impact data that most accurately reflect the impact experienced by the real human body; two IMUs are required for bilateral detection. The final method, called S-method, entails analysing the resultant acceleration from an IMU at foot (or shoe) level. The peak indicates IC, and a threshold of 2*g* (g = gravitational acceleration) in the region of interest indicates TO (Fig. 1) [8]. As this method utilises resultant acceleration, errors induced by misalignment of axes could be minimized [18,19].

In addition to the IMU location, locomotion speed is related to impact acceleration and may thus affect the accuracy of the detected IC and TO. Although direct supporting evidence is unavailable, studies have reported that the difference in stance time (ST; estimated using IC and TO) observed using an IMU were 0 (± 12) ms for jogging, 2 (± 3) ms for running, and 1 (± 1) ms for sprinting [21]; 16–25 ms for running at slow, natural, or fast speed [3]; and 26–103 ms for walking at speeds of 0.5-1.75 m/s [4]. In these studies, the accuracy of the detected IC and TO was indeterminate.

Because typical methods for identifying IC and TO involve IMUs affixed to various anatomical locations, the present study compared (a) the aforementioned three methods during overground jogging and running, (b) time differences in IC and TO detection through the various methods, and (c) accuracy of the estimated ST. An optimal method for estimating ST was proposed, and supporting evidence is provided in this paper to serve as a reference for future running-related studies regarding where an IMU should be positioned on the human body.