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Quantitative estimation of foot-flat and stance phase of gait using foot-worn inertial sensors

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ABSTRACT

Time periods composing stance phase of gait can be clinically meaningful parameters to reveal differences between normal and pathological gait. This study aimed, first, to describe a novel method for detecting stance and inner-stance temporal events based on foot-worn inertial sensors; second, to extract and validate relevant metrics from those events; and third, to investigate their suitability as clinical outcome for gait evaluations. 42 subjects including healthy subjects and patients before and after surgical treatments for ankle osteoarthritis performed 50-m walking trials while wearing foot-worn inertial sensors and pressure insoles as a reference system. Several hypotheses were evaluated to detect heel-strike, toe-strike, heel-off, and toe-off based on kinematic features. Detected events were compared with the reference system on 3193 gait cycles and showed good accuracy and precision. Absolute and relative stance periods, namely loading response, foot-flat, and push-off were then estimated, validated, and compared statistically between populations. Besides significant differences observed in stance duration, the analysis revealed differing tendencies with notably a shorter foot-flat in healthy subjects. The result indicated which features in inertial sensors' signals should be preferred for detecting precisely and accurately temporal events against a reference standard. The system is suitable for clinical evaluations and provides temporal analysis of gait beyond the common swing/stance decomposition, through a quantitative estimation of inner-stance phases such as foot-flat.

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1. Introduction

In clinical gait evaluation, stance phase is defined as the period of time where the foot is in contact with the ground [1]. Stance has been also described as a succession of different sub-phases such as loading response, mid-stance, terminal stance and pre-swing [2]. Gait changes in elderly persons have been characterized by a longer foot-flat [3]. Those previous studies show that quantitative assessment of sub-phases of stance (referred as "inner-stance phases"), such as foot-flat, can bring additional insight into clinical gait assessment.

Stance phase has been detected using stationary devices such as optical motion capture, force-plate [4] and electronic walkways embedding pressure sensors [5]. Ambulatory devices such as footswitches [6], pressure insoles [7], accelerometers [8,9], gyroscopes [10,11], and combinations of inertial sensors and pressures sensors [12,13] were also used for this purpose. Applications range from the real-time triggering of electrical stimulators to the estimation of temporal parameters that have shown to be relevant for various clinical evaluations such as frailty in the elderly [10,14] or motor symptoms in Parkinson's disease [15].

Using ambulatory measurements for temporal analysis, information can be reliably derived from large datasets collected in natural long-distance gait. Nevertheless, in most previous studies, stance phase was considered as a single block without any subdivision from heel-strike to toe-off [6,9–11,16]. On the other hand, studies that considered inner-stance phase events [8,12,13], did not assess thoroughly the technical validity of their method in terms of temporal precision and accuracy against a gold standard. A detailed study of the reliability of gait events detection from various inertial sensors was recently proposed [17], but the authors mainly focused on the sensitivity and specificity of detection when using Foot Sensitive Resistors and on a limited population, rather than on temporal precision and accuracy.

The goal of this paper was two-fold. First, it aimed to show a novel method based on foot-worn inertial sensors to detect temporal events based on robust features of foot kinematic patterns, and extract inner-stance phases defined between pairs of successive events. As a technical validation, the performance of our

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method was compared to force reference measurements on a two-segment foot model. Second, we tested the efficacy of inner-stance phase estimates as a potential outcome measure for clinical gait evaluations, by using the system to compare healthy control subjects to age-matched patients suffering from ankle disease during a 50-m gait test.

2. Method

2.1. Measurement devices and sensor configuration

Ambulatory pressure insoles (Pedar-X, Novel, DE) were used as a reference system to measure the contact time of different regions of the foot with the ground. This pressure sensor technology has shown high linearity, low creep, low hysteresis, and low variability for all performances over the whole sensor matrix [18]. Additionally, it has been reported as accurate and reliable in gait measurements compared to force-plate [7] and repeatable in different foot regions and on different days [19]. Finally, Pedar insoles have been successfully used instead of force-plate for force measurement during gait [20] and clinical evaluation based on temporal and pressure parameters [21]. Therefore, Pedar pressure insoles were considered as a validated reference for this study. Subjects wore the pressure insoles embedded in custom-made shoes (Fig. 1). One inertial measurement unit (IMU) consisting of 3D gyroscopes and 3D accelerometers was installed on the forefoot over the bases of first and second metatarsals, such that one gyroscope, referred to as pitch, was aligned to foot's sagittal plane (Fig. 1). The IMU was connected to a portable data-logger (Physilog, BioAGM, CH) with an internal low-pass analog filter (17 Hz). Both pressure insoles and IMU devices recorded signals synchronously at 200 Hz.

2.2. Temporal events detection

Stance phase is the period between initial contact, referred to as Heel-Strike (HS), and terminal contact, referred as Toe-Off (TO). Additionally, stance encapsulates the instant where toes touch the ground and make the foot land flat, referred as Toe-Strike (TS), and the instant where the heel rises from the ground, referred as Heel-Off (HO). {HS, TS, HO, TO} are defined as the temporal events of stance (Fig. 2a).

2.2.1. Kinematic features from inertial sensors signals

During one stride, the two negative peaks of pitch angular velocity of shank are known to be robust approximate estimates of HS and TO on both healthy and patient populations [10,22]. Foot pitch angular velocity (Ω_p) shows similar negative peaks for HS and TO. Consequently, those peaks were detected and used to split gait trials into cycles and define limited time windows for further robust detection of the

Fig. 1. Sensor configuration worn by a subject with inertial measurement unit (IMU) fixed on forefoot and pressure-insoles (reference system) beneath the foot.

kinematic features. Candidate features for detecting HS and TO were identified by the minimum (MIN), maximum (MAX) and zero-crossing (ZERO) time sample of the three following signals: Ω_p, the norm of 3D accelerometer signal ($||A||$) and the derivative of 3D gyroscope signal norm ($||\Omega||'$), where $||X||$ is the Euclidian norm of vector X.

The phase between TS and HO, so-called foot-flat, is characterized by a lower amount of movement since the ground constrains the foot. So, candidate features for detecting TS and HO were identified by the first and last sample for which signals of $||\Omega||'$, Ω_p, and the absolute value of the derivative of accelerometer signal's norm ($|||A||'|$), were below a specific threshold. Signals norms were preferentially selected in order to be independent of IMU positioning. All these detection rules, and the six subsequent kinematic features extracted for each event are detailed in Table 1 and illustrated in Fig. 2b and c.

2.2.2. Reference force features from pressure insole signals

A foot frame was defined with its X-axis as the horizontal projection of vector from the great tuberosity of calcaneus to the head of second metatarsal, Y-axis to the left and Z-axis upwards. The foot was divided into two segments: hindfoot and forefoot, and the coordinates of the 99 sensor cells of the insole were determined. Sensors cells with X-coordinate lower than the midpoint between bony landmarks of the navicular and cuboid bones were assigned to hindfoot, while other sensor cells were assigned to forefoot. The vertical force exerted on each segment (F) was

Table 1
List of features and their differences among 3193 recorded gait cycles. Temporal events are detected based on signal from inertial sensors (k_1 to k_{24}) and pressure insoles (f_1 to f_4). Ω_p and $||\Omega||'$ correspond to the pitch angular velocity of the foot and the derivative of the norm of foot angular velocity. $||A||$ and $|||A||'|$ correspond to the norm of foot acceleration and its absolute derivative. F_h and F_f are the vertical force signals estimated on the hindfoot and forefoot segments. Minimum value of differences for each event is indicated in bold italic.

	Kinematic			Force			Difference (ms)			
	Signal	Rule	Feature	Signal	Rule	Feature	Mean	MAE	STD	MAD
Heel-Strike	Ω_p	MIN	k_1	F_h	>5% of BW	f_1	29	26	*8*	*6*
		0	k_2				−39	43	17	13
	$\|\|A\|\|$	MIN	k_3				*1*	*8*	13	9
		MAX	k_4				37	36	14	8
	$\|\|\Omega\|\|'$	MIN	k_5				36	43	32	18
		MAX	k_6				−6	12	13	10
Toe-Strike	$\|\|\Omega\|\|'$	< -0.02 rad/s^2	k_7	F_f	>5% of BW	f_2	74	73	52	42
		< -0.06 rad/s^2	k_8				24	44	52	39
	Ω_p	> -1 rad/s	k_9				−23	41	44	38
		> -2 rad/s	k_{10}				*−4*	*31*	*37*	*31*
	$\|\|\|A\|\|'\|$	< 0.05 m/s^3	k_{11}				75	74	49	36
		< 0.2 m/s^3	k_{12}				12	47	53	45
Heel-Off	$\|\|\Omega\|\|'$	> -0.02 rad/s^2	k_{13}	F_h	<5% of BW	f_3	*4*	*41*	54	40
		> -0.06 rad/s^2	k_{14}				60	73	66	50
	Ω_p	< -1 rad/s	k_{15}				76	81	*51*	*36*
		< -2 rad/s	k_{16}				121	130	63	45
	$\|\|\|A\|\|'\|$	> 0.05 m/s^3	k_{17}				113	125	87	61
		> 0.2 m/s^3	k_{18}				169	176	71	50
Toe-Off	Ω_p	MIN	k_{19}	F_f	<5% of BW	f_4	−33	35	14	11
		0	k_{20}				63	65	21	17
	$\|\|A\|\|$	MIN	k_{21}				−81	85	15	11
		MAX	k_{22}				*−3*	*11*	*13*	*9*
	$\|\|\Omega\|\|'$	MIN	k_{23}				5	22	22	21
		MAX	k_{24}				−70	71	18	12

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