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The largest inertial sensor-based gait database and performance evaluation of gait-based personal authentication

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ABSTRACT

This paper presents the largest inertial sensor-based gait database in the world, which is made open to the research community, and its application to a statistically reliable performance evaluation for gait-based personal authentication. We construct several datasets for both accelerometer and gyroscope of three inertial measurement units and a smartphone around the waist of a subject, which include at most 744 subjects (389 males and 355 females) with ages ranging from 2 to 78 years. The database has several advantages: a large number of subjects with a balanced gender ratio, variations of sensor types, sensor locations, and ground slope conditions. Therefore, we can reliably analyze the dependence of gait authentication performance on a number of factors such as gender, age group, sensor type, ground condition, and sensor location. The results with the latest existing authentication methods provide several insights for these factors.

1. Introduction

Recently, smart wearable or portable electronics are being developed so rapidly, and they are expected to be sophisticated enough in the future to be able to interact with the owner and understand his/her needs, intentions, actions [1,2], and health conditions [3,4]. Inertial sensor (accelerometer or gyroscope) is in fact increasingly being embedded in commercial portable electronic devices such as smartphones due to their high cost-performance, and inertial sensor-based owner assistance, such as user recognition, is an active research topic.

There are many existing methods to recognize a person who carries an inertial sensor based on gait such as identification by [5–9] or verification by [8,10–16], which showed the promising applications of inertial sensor for gait-based recognition.

Because the human gait is a periodic motion, a large number of gait recognition methods detect periods [5,6,9,12,13,15,17] for constructing gait patterns. Some researchers use frequency-domain features such as a histogram of signal intensity [8,10] or coefficients of Fourier transform [6,7]. Some researchers employs model-based approaches [18,19], in which gait signal is modeled using a finite state machine.

However, in these studies, the authors evaluated their methods with databases limited in number of subjects, age variety, gender balance, sensor types, and ground conditions and hence the reliability of the performance evaluation is insufficient. In addition, it is difficult to compare these methods because they lack a common ground such as the same sensor configuration, gender ratio, number of subjects, and ground condition.

In this paper, the first contribution is to construct the largest inertial sensor-based gait database in the world to overcome such limitation. The advantages of the database includes (1) a very large number of subjects (744), (2) a balanced gender ratio, (3) a wide age range (2–78 years), (4) both acceleration and angular velocity data captured by three inertial sensors (containing both accelerometer and gyroscope) and a smartphone (containing an accelerometer), (5) a variation of sensor locations on subject's waist, and (6) 3 ground slope conditions (walking on a flat ground, walking up, and down a slope). The second contribution is to evaluate the state-of-the-art gait authentication algorithms in a more statistically reliable way and to reveal how gait authentication performance differs between genders and among age groups, sensor types, and sensor locations using the database. This paper is an extended version of our previous publication [20]. Here, we present an extended database with variations of sensor location, sensor type, and ground slope so that we can conduct more experiments with more comprehensive results.

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2. Related work

2.1. Existing inertial gait databases

There are many databases have been used in this field as summarized in Table 1, however they are publicly unavailable for the research community.

The largest existing database was used by Gafurov et al. [23] with 100 subjects, the gender is biased with a number of males is twice larger than that of females. This database was frequently used to evaluate the algorithms within the same research group [23–25,31]. Derawi et al. [15], Kobayashi et al. [7], Gafurov et al. [22,31], and Jenifer et al. [8] evaluated their methods with databases of 60, 58, 50, and 36 subjects, respectively, without age and gender information. Derawi et al. [27] again captured another dataset of 51 subjects with a very biased gender ratio and age distribution.

The largest database for smartphones was presented by Kobayashi et al. [7] with 58 subjects and about 40 sequences per subjects on different days. However, the frame-rate was as low as 33 Hz.

In overall, the numbers of subjects in these databases (100 subjects at most in [23]) are insufficient for statistically reliable performance evaluation. In addition, age variety is limited to adult and/or gender balance is biased.

2.2. Recognition methods

As stated above, since gait signal is periodic, there are three main approaches for gait recognition: period detection-based, frequency analysis-based, and gait model-based methods.

A large number of recognition systems [5,6,9–17] detect gait periods, each of which contains motion signal of both left and right steps, to construct gait patterns for recognition. A gait period can be detected from a gait signal sequence using heuristic information [5,12,13,15], or without heuristic information [16].

Some researchers use frequency-domain features such as a histogram of signal intensity [6,8,10], or coefficients of Fourier transform [6,7]. To obtain such frequency-domain features, we need a relatively long and stable gait signal sequence. However, a real gait signal is very noisy, temporally distorted and sensor orientation may change, and hence such a long stable gait signal is rarely available. As a result, frequency analysis-based techniques are outperformed by period detection-based methods in most situations [6,14,16]. Moreover, period detection-based methods can be applied for a single period of signal sequence (about 1 s), which implies potential real-time applications, while the frequency analysis-based methods cannot.

In the gait model-based methods [18,19], a gait model is generated using a finite state machine then some characteristics such as the gait period symmetry and homogeneity are used for gait pattern. However, the gait model-based methods require expert knowledge about the human gait to train the finite state machine so that it cannot deal well with the signal variation either.

In the evaluation of the gait authentication with our database, we select the four latest period detection-based authentication methods presented by four other research groups for evaluation with our database.

3. Gait database construction

3.1. Setup of gait capture system

To consider variations of sensor type and sensor location, we used four sensors to capture gait signals: three IMUZ sensors from ZMP Inc. [32], and a triaxial KXTF9 accelerometer from Kionix Inc. [33] inside a

Table 1
Existing inertial gait databases.

Research work	# Subjects	Age/gender	Sensor and data description
[15]	60	NA (not available)	Accelerometer at left hip, 12 sequences/subject
[5,6]	36	Adults, 17 females and 19 males	Accelerometer at waist, different days, fast, slow, and normal speeds
[21]	31	19 Males and 12 females	2 Sequences/subject, accelerometer at hip pocket, breast pocket and hand-held
[22]	50	NA	Accelerometer in trousers pocket
[23–25]	100	70 Males and 30 females, aged between 19 and 62 years	Accelerometer at right hip, 4 sequences/subject
[12]	30	NA	16 Sequences/subject, accelerometer at ankle, four shoe types
[26]	9	NA	Both accelerometer and gyroscope attached on shoe
[14]	21	10 Males and 11 females at ages between 19 and 40 years	Accelerometer at center of back waist, 5 sequences on different days
[13]	35	19 Males and 16 female, aged between 20 and 45 years	Accelerometer, 5 sequences/subject
[27]	51	41 Males and 10 females at ages of 20 s and 30 s	2 Days $\times$ 2 sequences/ subject
[8]	36	NA	Accelerometer in pocket
[28]	9	NA	Smartphone at subject's hip, 2 sequences on two days
[7]	58	NA	Accelerometer worked at 33 Hz in the hand-held iPhone, 40 sequences/subject on different days
[29]	48	38 Males and 10 females at ages mostly between 20 and 30 years	Smartphone at hip, 2 sequences on 2 days
[16]	32	7 Females and 25 males at ages of 21 to 40 years	Gyroscope, 5 sequences/subject with different attached weights
[19]	20	15 Males and 5 females at ages of 23 to 52 years	Accelerometer at center back, 10 datasets of 5 gait cycles for each subject
[30]	36	28 Males and 8 females at ages mostly between 22 and 28 years	Accelerometer in the right trouser's pocket, up and down a hallway, normal and fast speed
Our database	744	389 Males and 355 females at ages of 2 to 78 years	3 Inertial sensors (accelerometer and gyroscope) and a smartphone (accelerometer) working at 100 Hz are located around the waist, 3 different ground slope conditions