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Intra-individual gait pattern variability in specific situations: Implications for forensic gait analysis

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ABSTRACT

In this study, inter- and intra-individual gait pattern differences are examined in various gait situations by means of phase diagrams of the extremity angles (cyclograms). 8 test subjects walked along a walking distance of 6 m under different conditions three times each: barefoot, wearing sneakers, wearing combat boots, after muscular fatigue, and wearing a full-face motorcycle helmet restricting vision. The joint angles of foot, knee, and hip were recorded in the sagittal plane. The coupling of movements was represented by time-adjusted cyclograms, and the inter- and intra-individual differences were captured by calculating the similarity between different gait patterns. Gait pattern variability was often greater between the defined test situations than between the individual test subjects. The results have been interpreted considering neurophysiological regulation mechanisms. Footwear, masking, and fatigue were interpreted as disturbance parameters, each being a cause for gait pattern variability and complicating the inference of identity of persons in video recordings.

1. Introduction

The objective of forensic gait analysis is the identification of persons based on their gait pattern, or the reduction of the size of a potential group of suspects based on exclusion. In contrast to personal identification through clothes [1,2], face [3–5], or other biometric modalities ([6,7], for a general description of forensic biometrics, see [8]), the manner of walking is used as an analysis criterion [9]. Surveillance videos allow the observation of biometric parameters, for example body height [10], leg lengths and body proportions [11], or physiological parameters, such as the movement of the extremities or coupling of partial movements. The first question coming to mind is the selection of suitable measurands useful for identification [12]. While biometric parameters describe a person's body in its dimensions, physiological parameters represent the actual basis for forensic gait analysis. It is assumed that the gait pattern has invariable, individual characteristics that enable unambiguous identification of different persons [13].

To quantify a person's gait pattern, individual parameters must be extracted, which are measurable and represent characteristic features [14]. For example, stride length, cadence, movement amplitudes, angle amplitudes, and angular speed represent applicable parameters [15–19].

Gait pattern analysis requires a multi-level examination procedure, during which suitable parameters describing the gait are extracted from CCTV or video footage. Gait is defined as a movement of the extremities in their joints. The positions of the relevant joints (shoulder, hip, knee, ankle, possibly also arms and head) must be reconstructed. Several research studies which were able to implement this with a defined accuracy [20,21] have already been conducted. The main issue here lays in the fact that the joints are usually covered by clothes [22]. Therefore, the movement of the joints underneath the garments can only be surmised from the movement of the clothes [23]. The distortion of perspective caused by the arrangement of the CCTV camera that usually films the test subject from a slanted angle can be adjusted quite accurately with the help of computer software [24,25]. Nevertheless, it is still a two-dimensional camera image that reconstructs a three-dimensional movement [26].

If the issues pertaining to measurement technology [27,28] and software analysis are solved, the next issue is how well gait patterns can be reproduced and identified. Reproducibility targets the question if one and the same person always exhibits the same gait pattern at specific times and under specific conditions [22,29], and identifiability is about the question whether it is possible to clearly differentiate the (reproducible) gait patters of multiple test

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subjects. Only if both questions are answered with yes, it is possible to deduce that the gait pattern represents a valid measurand to identify persons and has biometric characteristics.

The objective of this study was the examination of inter- and intraindividual differences of gait patterns in different gait situations by means of phase diagrams of extremity angles (cyclograms) in order to be able to deduce conclusions on the suitability of gait pattern analysis for the identification of persons.

2. Material and methods

2.1. Walkway

The tests took place in a biomechanics laboratory where the test subjects (5 males, 3 females) walked along a walkway approximately 6 m long at a speed they selected. White cardboard was used to delimit a 3 × 2 m wide area to provide a high-contrast background for the video recordings.

2.2. Measuring technology

A digital video camera (Sony HDR-XR 520, 1920 × 1080 pixels spatial resolution, 50 frames per second temporal resolution) mounted on a tripod at a distance of 5 m at a height of 1.50 m captured a section of approx. 4 m width in the middle of the walkway. The camera axis was aligned orthogonally to the test subject and surface in order to minimize parallactic distortion.

2.3. Marking of the joints

Easily visible flat markers with a diameter of 15 mm each were attached to representative joints on the left side of each test subject's body on the skin or tight-fitting clothes. Table 1 shows the individual anatomic landmarks.

Both measuring technology and measuring conditions are clearly better than what can be expected in forensic circumstances.

2.4. Test variants

A total of five different test variants performed by all test subjects were measured and recorded.

Barefoot: to measure a natural gait pattern, i.e., not influenced by footwear, these sub-tests were performed barefoot or wearing socks.

Sports shoes: the test subjects wore customary sports shoes. The marker for the 5th metatarsal was affixed to the shoe after palpation.

Full-face helmet: a full-face motorcycle helmet was worn to simulate restricted vision. The test subjects wore sports shoes.

Combat boots: since footwear extending up beyond the ankles restricts movement in the upper ankle joint and therefore presumably changes the gait pattern, the test subjects wore combat boots in these sub-tests.

Fatigue: briefly before the tests, the front thigh muscles (M. quadriceps femoris) were strained on a leg press with slow, concentric and eccentric movements without a break until complete exhaustion was reached. Men had to press a weight of 60 kg, and women had to press 35 kg. Between 20 and 84 repetitions were performed, depending on the individual. Directly thereafter, the tests with sports shoes were carried out on the walkway.

2.5. Test procedure

The test procedure is a lot more constrained than what can be expected in forensic conditions.

On a command from the examiner, the test subjects walked the walkway at a self-defined, average speed, starting from a standing position and looking toward the opposite wall. Each sub-test was repeated three times by all test subjects, before they continued to the next sub-tests. The digital video files recorded were saved to a computer.

2.6. Data processing and analysis

The video evaluation was performed using the Dartfish ProSuite 6.0 software. As soon as the test subject stepped on the area marked with white cardboard with the left heel ("initial contact phase"), the markers on skin and garments were manually marked in the video frame. Via a tracking algorithm, the software traced the shifting of the marker points from frame to frame and thus generated plottable trajectories of each marker point.

In contrast to other studies, in which the angles of the leg joints as a function of time were examined as a characteristic criterion [30], this study is about representing the combination of joint angles in a time-independent phase space. To implement this, the left leg's foot, knee, and hip angle was determined by means of the Matlab software (Vers. R2013a, MathWorks Inc.), and the joint angles for a specific point in time were compared in a coordinate system. This resulted in cyclograms with each point representing a combination of two angles at a specific point in time (Fig. 1).

This type of representation has an advantage over the plotting of joint angles over time: the time-independent coupling of the joint movements is shown. Using the three angles calculated it would be possible to create a three-dimensional angle trajectory. However, for reasons of easier comparability, only two angles were plotted against each other (foot-knee, knee-hip).

A total of 9 steps per test were evaluated in this way, and the envelope curve of the 9 cyclograms was defined as a confidence interval. Similarity between two sub-tests was calculated based on the percentage amount of points when both confidence intervals CI did not overlap.

For calculating similarity S_{a-b} between patterns a and b we used the formula

$$S_{a-b} = (n_{\text{total}} - n_{\text{diff}})/n_{\text{total}} * 100 \ [\%]$$

with $n_{\text{diff}} = |\{P(n)|\text{CI}(n_a) \cap \text{CI}(n_b) = \phi\}|$, n_{total}: number of calculated points, n_{diff}: number of points when confidence intervals do not overlap, and $\text{CI}(n_{a/b})$: confidence intervals for patterns a and b at point n.

If, for example, a measurement consists of 50 points and for 12 points the confidence intervals do not overlap, the similarity would be (50–12)/50 * 100 = 76%.

Table 1
Positioning of marker points and calculated angles.

Joint	Anatomic landmark	Joint angle		
Shoulder	Acromion	*		
Hip	Trochanter major	*Hip angle	*	
Knee	Epicondylus humeri lateralis	*	* Knee angle	*
Ankle	Malleolus lateralis		*	* Foot angle
Toe	Articulatio metatarsophalangea D5			*