Ultrasonic motion analysis system—measurement of temporal and spatial gait parameters

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Abstract

The duration of stance and swing phase and step and stride length are important parameters in human gait. In this technical note a low-cost ultrasonic motion analysis system is described that is capable of measuring these temporal and spatial parameters while subjects walk on the floor. By using the propagation delay of sound when transmitted in air, this system is able to record the position of the subjects' feet. A small ultrasonic receiver is attached to both shoes of the subject while a transmitter is placed stationary on the floor. Four healthy subjects were used to test the device. Subtracting positions of the foot with zero velocity yielded step and stride length. The duration of stance and swing phase was calculated from heel-strike and toe-off. Comparison with data obtained from foot contact switches showed that applying two relative thresholds to the speed graph of the foot could reliably generate heel-strike and toe-off. Although the device is tested on healthy subjects in this study, it promises to be extremely valuable in examining pathological gait. When gait is asymmetrical, walking speed is not constant or when patients do not completely lift their feet, most existing devices will fail to correctly assess the proper gait parameters. Our device does not have this shortcoming and it will accurately demonstrate asymmetries and variations in the patient's gait. As an example, the recording of a left hemiplegic patient is presented in the discussion. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

In human gait a complete stride cycle can be divided into a stance phase and a swing phase. Within these phases two other periods can be distinguished, the double support and the single support phase. Closely linked to these temporal parameters are the spatial parameters step length and cycle length (stride length) (DeVita, 1994; Inman et al., 1981). These important kinematic parameters of the human gait can be determined by measuring the position of the feet during walking. By relating these positions to time, both spatial and temporal parameters can be determined.

Several methods have been presented to determine the length and duration of these phases (Crouse et al., 1987; Holden et al., 1984; McDonough et al., 2001; Peham et al., 1999; Rigas, 1984). However, problems arise when both the spatial and temporal parameters have to be recorded in subjects with a pathological gait pattern. If patients do not completely lift their feet, techniques using electrical contacts or foot switches do not work properly. Techniques using cameras and markers are restricted in their range of view. Furthermore, these methods are very expensive and the data analysis is complex.

The aim of this study was to develop an ultrasonic motion analysis system that is capable of measuring temporal and spatial gait parameters. The range in which this device can be used should be in accordance with the dimensions of a common gait lab so that subjects can walk on the floor.

2. Methods

2.1. Ultrasonic distance measurement

In order to separately assess both step length and duration, the actual position of the feet during walking

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has to be recorded. For this an ultrasonic device is used. The device consists of two transmitters, one on either side of the gait lab, and two receivers, one on each foot. Only one transmitter is used at a time, depending on the direction of walking. The transmitter sends out a burst of ultrasound and the delay it takes for this burst to reach the receiver is recorded. From this delay the distance between the transmitter and the receiver can be calculated from

$$d = tv_s, \tag{1}$$

where d is the distance in meters, t is the propagation delay in seconds and v_s is the velocity of sound waves in air. Sound velocity can be approximated by

$$v_s = 331.5 + 0.6T_c, \tag{2}$$

where T_c is the air temperature in degree centigrade.

Fig. 1 represents a block diagram of the ultrasonic device. The ultrasonic burst consists of 8 pulses with a frequency of 40 kHz. In order to avoid ambiguous measurements, it is necessary to wait with transmission of another ultrasonic burst until the previous one has been received. The device is set to transmit bursts every 25 ms, making the maximum distance about 8.6 m. The propagation delays for both receivers are measured using a 12-bit counter that reaches full range in 25 ms, resulting in a theoretical resolution of 2.1 mm (8.6 m/2^{12}). The 12-bit counter starts counting the moment a burst is transmitted. Its output is stored and immediately converted to an analog output signal when the transmitted burst is received by an ultrasonic receiver. This asynchronous D/A conversion eliminates time lag errors that would occur if D/A conversion had been triggered synchronously by the burst generator. The

input signal processor eliminates most noise from the input signal by lowpass filtering and testing if the signal consists of a minimum of 8 pulses. Furthermore, it disables the input after a valid signal is received for the remaining part of the 25 ms period.

2.2. Subjects

Four healthy subjects, two males and two females, were used to test the device. Ages of the subjects were 22, 27, 30, and 49. The subjects were informed about the procedures of the experiment and approved to these.

2.3. Procedure

Subjects wore regular shoes without high heels. The ultrasonic receivers were attached on top of the shoes pointing forward, using textile adhesive tape. The receivers were connected to a small terminal box the subjects wore on a belt. From this terminal box a cable led back to the transmitter. To be able to validate the temporal parameters, electrical foot contact switches were used. These switches consisted of two pieces of conductive adhesive tape, attached to the front and the back of the sole of each shoe, in combination with an aluminum walkway. By applying a low voltage to the walkway, contact with the conductive tape could be detected and the moment of heel-strike and toe-off recorded. Each subject walked six times way and forth: twice at comfortable speed, twice at high speed and twice at low speed.
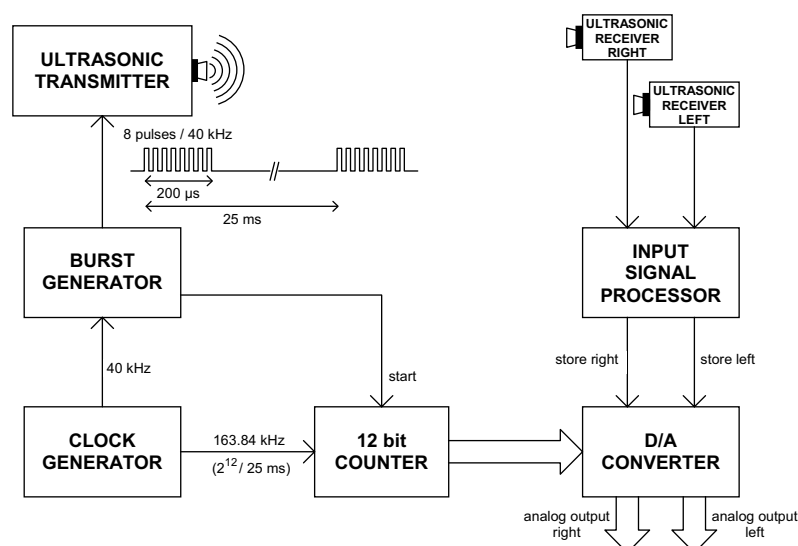

Fig. 1. Block diagram of the ultrasonic gait analysis system.

2.4. Data processing

Data were recorded using a 200 Hz sampling frequency. Despite the thorough noise reduction by the input signal processor some artifacts still occurred, probably due to temporary occlusion of a receiver. However, detecting steep changes in the output signal and interpolating the signal at these points could easily remove these few artifacts. The signal was smoothed using a second-order zero-phase forward and reverse digital Butterworth lowpass filter with a 20 Hz cut-off frequency. To calibrate the device, data were recorded for each receiver at 7 static points (1, 2, 3, 4, 5, 6, 7 m). By means of a linear regression this resulted in two scaling equations (one for each receiver) for converting the signal from voltage to meters.

3. Results

Fig. 2 shows the processed data in the normal speed walking condition for one subject (male, 30 yr). It is seen that step and stride length can easily be determined by subtracting positions of the foot with zero velocity.

In Fig. 3 both position and speed of one step are presented. The speed of the foot was calculated by differentiating the position graph, after which a second-order zero-phase forward and reverse digital Butterworth lowpass filter with a 5 Hz cut-off frequency was applied.

By comparing the speed graph to the data recorded by the foot contact switches in the three speed conditions and for all subjects, it appeared that in all conditions and for all subjects toe-off and heel-strike could be calculated from the speed graph by applying two thresholds. These thresholds were relative to the maximum speed of the foot within one step, V_{max}. For toe-off the threshold was at 30% of V_{max} (sd: 0.029) and for heel-strike it was at 35% of V_{max} (sd: 0.054).

The values of toe-off and heel-strike calculated by applying these thresholds were compared to the data recorded by the foot contact switches. The difference between these measurements was considered an error and the average (rms) and maximum errors for all subjects are presented in Table 1.

4. Discussion

The ultrasonic device presented in this study is capable of reliably measuring temporal and spatial parameters in gait. Step and stride length can be determined by subtracting positions of the foot at positions with zero velocity. Duration of stance and swing phase can be determined by calculating heel-strike and toe-off and duration of double support phase by combining heel-strike and toe-off from both feet. The errors observed in heel-strike and toe-off, as reported in Table 1, are random errors and are mostly due to the repetition rate of the ultrasonic device (40 Hz; 25 ms).
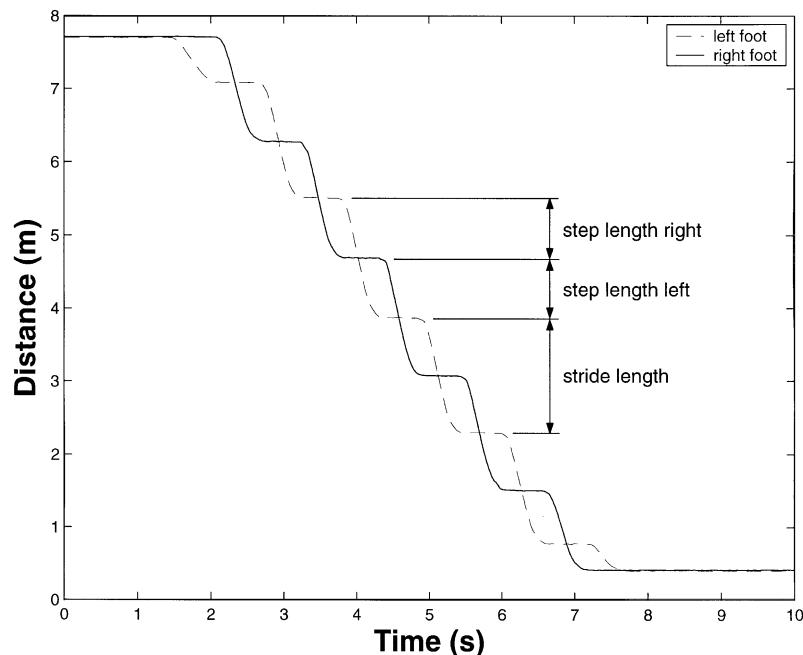

Fig. 2. Position of feet of a typical subject walking at normal speed. Step and stride length can be determined by subtracting the positions of the foot with zero velocity.
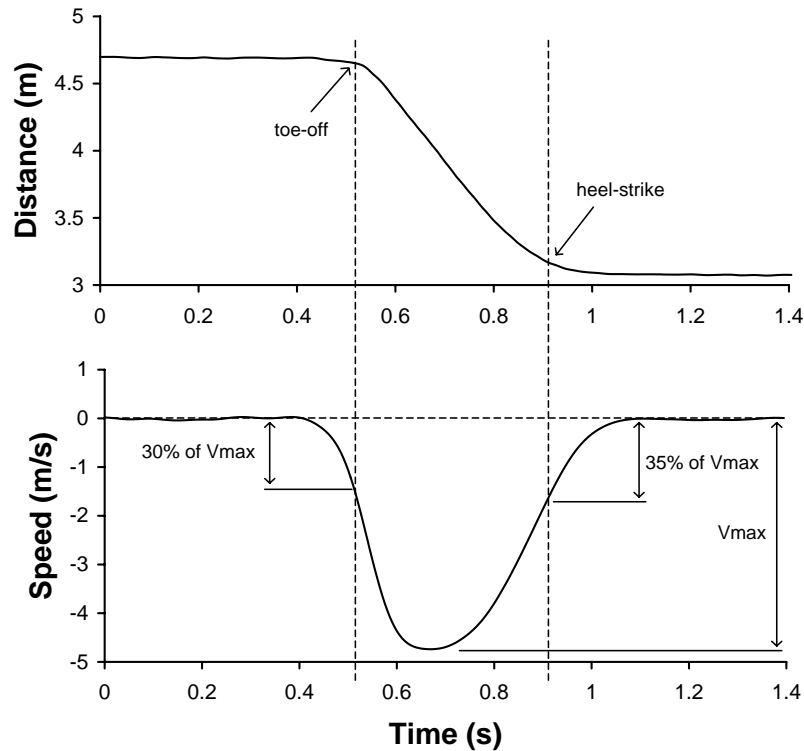
Fig. 3. Toe-off and heel-strike can be calculated by differentiating the position graph and applying two different thresholds. When the speed of the foot raises above the level of 30% of V_{max} (the maximum velocity the foot reaches within a step), toe-off occurs. Heel-strike occurs when the velocity drops below 35% of V_{max}.

Table 1
Average and maximum error in toe-off and heel-strike when comparing the ultrasonic device with foot contact switches. The average error is calculated as an rms. The reported speed for each condition is the average speed of all subjects

Condition (m/s)	Toe-off		Heel-strike	
	Avg. error (ms)	Max. error (ms)	Avg. error (ms)	Max. error (ms)
Slow (0.85)	21.9	60	31.4	55
Normal (1.35)	10.8	25	12.4	35
Fast (1.91)	8.88	25	12.0	25

Furthermore, this error results from the comparison of the ultrasonic measurements with data obtained from foot contact switches. Obviously, these foot contact switches will introduce an error of their own, thus the actual errors of the ultrasonic measurements are smaller than those reported.

Compared to the method by Peham et al. (1999), using high-speed video recordings to determine the stance phase in horses' gait, the reported error in toe-off and heel-strike appears to be rather large. However, this is mainly due to the fact that they analyzed horses' gait. The transitions between stance and swing in these gait patterns are steeper as they are in gait patterns of humans (as can be seen in Fig. 3 in their article), making the detection of these moments more reliable for horses' gait. The higher sample rate applied by Peham et al.

(240 Hz compared to 40 Hz in our device) will also increase their reliability. A disadvantage of the use of cameras for the determination of gait parameters is the rather limited range. Common camera-based gait analysis systems are usually limited to a maximum range of about 3 m. Our device has a maximum range of about 8 m which makes it possible to perform gait analysis on the floor rather than being limited to treadmill analysis. Further disadvantages of a camera-based system, compared to our device, are its rather complicated usage and data analysis and the high costs of the system. However, our device is of course more limited in the parameters it can measure when compared to a camera-based system.

A system which is also capable of measuring both spatial and temporal parameters in gait is the GAITRite™
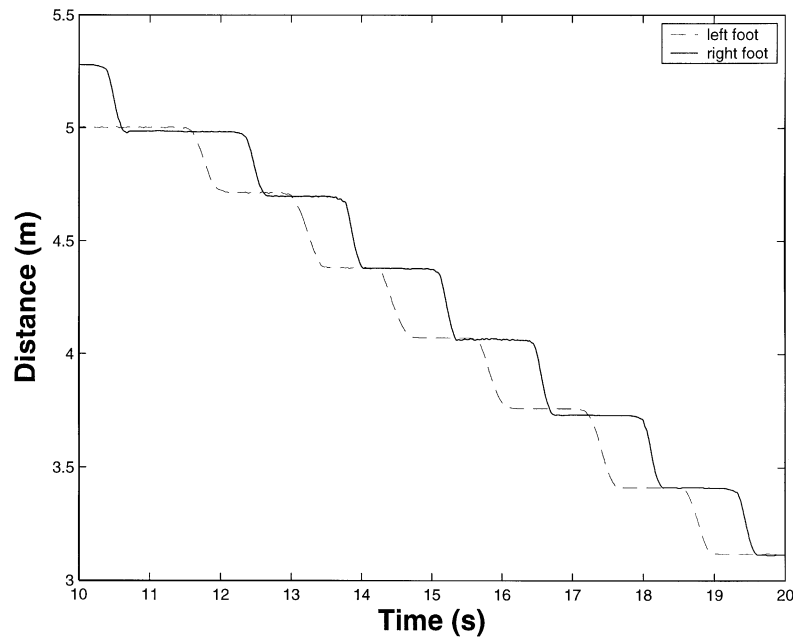
Fig. 4. Gait analysis of left hemiplegic patient. A lag of the right, non-paretic leg and an asymmetry in both swing and stance phase can be observed.

system (McDonough et al., 2001). This system uses a 3.7 m long walkway with a grid of embedded pressure-sensitive sensors. The length of this walkway can be doubled by using two walkways. By detecting when a foot makes contact with the floor, this system is capable of measuring the exact moments like heel-strike and toe-off. Since our device infers these moments from the speed of the foot, it is to be expected that the GAITRite system will be more reliable in measuring these parameters. However, the maximum sample rate of the GAITRite system is 80 Hz, which will limit its superiority. As for the spatial parameters, the GAITRite system has a resolution of 1.27 cm compared to 2.1 mm for our device, making our device superior for this parameter.

Most existing low-cost devices, like foot contact switches, infer step and stride length from the step and stride time, assuming a constant walking speed. When gait is asymmetrical or when walking speed is not constant this will result in incorrect measurements. Since our ultrasonic device records the actual position of the feet these errors will not occur; on the contrary, it will accurately display the asymmetry.

The data reported in this paper are based on healthy subjects. However, this device promises to be extremely valuable in examining pathological gait since our device can accurately display asymmetries in gait patterns. An example is shown in Fig. 4, which is the recording of a left hemiplegic patient.

It clearly demonstrates that the non-paretic leg is lagging behind in position: when a step is made with the

non-paretic leg, the foot does not pass the supporting foot (of the paretic side) but is placed next to it. It further shows asymmetries in both swing and stance phase: a prolonged double support phase preceding the swing phase of the non-paretic leg and a relatively short single support phase of the paretic leg. These data are consistent with reported data of similar patients (De Quervain et al., 1996; Knutsson and Richards, 1979).

Although this device was originally designed for measuring gait while subjects walk on the floor it can also be used perfectly well in combination with a treadmill. Its unique measurement possibilities and the ease of use both in application to the subjects and in analysis of the data may make this ultrasonic motion analysis system a valuable addition to the gait lab.

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