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Simple gait assessment system

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Abstract

Continuous monitoring and frequent measuring of a patient's gait is essential for efficient rehabilitation so that corrective training measures can be adopted throughout the rehabilitation process. Important parameters in gait evaluation are the instantaneous horizontal velocity of the center of gravity (COG) and the overall distance covered. We describe a simple gait assessment system based on combined ultrasound (US) and infra red light (IR) distance/velocity measuring device. The device achieves 0.5% static accuracy within a 10 m range at 25 Hz sampling rate. The system functionality and feasibility was verified in two types of walking: normal gait and functional electrical stimulation (FES) assisted paraplegic gait. © 1997 Elsevier Science B.V.

Keywords: Gait evaluation; Rehabilitation; Distance and velocity measurement; Ultrasound

1. Introduction

Continuous monitoring and frequent measuring of a patient's gait is essential for efficient rehabilitation. Corrective training measures are adopted throughout the process for achieving improved walking results.

Gait evaluation represents the basis for locomotor rehabilitation. However, a thorough quantitative evaluation of walking is usually performed with costly motion analysis systems that are impractical or even unavailable in daily routine work. Therefore, many different and simplified techniques have been proposed and used for assessment of human gait. Basically, these methods employ a reduced set of sensors that provide a limited set of data. The raw gait sensory data are then extrapolated utilizing our *a priori* knowledge of locomotion. Such devices are also known as gait computers [1].

Important parameter for such gait evaluation is the instantaneous horizontal velocity/acceleration of the center of gravity (COG) and the overall distance covered [2]. For this purpose a distance/velocity measuring device is required. Several choices are available. Based on a COG distance/velocity measuring device combined with other measuring hardware, a simple gait computer can be designed.

Segment by segment approach is required to calculate the actual COG position and velocity [3]. This approach is possible only by utilizing complex motion analysis systems which we are trying to avoid. Therefore, we propose a simple distance/velocity measuring system for the assessment of the movement of the center of body (COB) as schematically shown in Fig. 1. We measure the COB progression to avoid sophisticated indirect measurements and mathematical calculations. Unlike the COG, the COB is a fixed anatomical quantity and is defined as COG in quiet standing. Its location is at the anatomical center of a cross-section of the body at the height of the second sacral vertebra [4]. As the COB is a fixed point, the distance/velocity assessment can be simplified without introducing significant systematic errors. This is particularly true for the stationary gait when the relationship between the COG and COB remains the same in each gait phase.

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The simplest approach for calculating velocity/distance measures makes use of a string attached between the subject's COB and a wheel mounted on a shaft of a tachometer or optical encoder [5]. The main drawbacks are mechanical limitations such as string oscillation and/or stretching as well as the subject's encumbrance but even this method can be optimized to achieve subcentimeter accuracy in up to 50 m walkway distances [6]. However, in a severely disabled person's gait, for example in the functional electrical stimulation (FES) assisted gait of a paraplegic subject [7], the COB can also move backwards [8]. It is virtually impossible to record this backward movement with a string based distance/velocity measuring device.

Alternative distance measuring methods are based on a two-axial accelerometer and inclinometer [9]. This method assumes that movement occurs mainly in the sagittal plane. The subject's encumbrance is significantly lower using this method however, calculating the distance or velocity is not as trivial as with the string based method. Another problem is accelerometer output offset. (This is a DC signal which is superimposed on the actual acceleration signal. Even a small accelerometer output offset can produce significant errors in velocity and distance as they are calculated by integrating the measured accelerations once or twice respectively.) This type of error is ever present and increases with time. Accelerometer output drift also causes similar problems.

There exist other distance/velocity measuring methods like gyroscopes [10] or goniometers [11]. These methods are either expensive, complicated, inappropriate or too cumbersome for our purposes.

To overcome the problems of the above mentioned measuring principles we have developed a contactless distance/velocity measuring system. A combination of ultrasound (US) and infrared light (IR) was chosen because of their advantages, proven in robotic applications [12] and mechanical engineering, where their utilization for proximity or obstacle detection/avoidance purposes is important. US is also used in some biological systems as a replacement for sight (for example, in bats, where US sensory system has radar like capabilities) [13].

2. Technology

The original specifications of the distance/velocity meter were defined having in mind the rehabilitation of spinal cord injured (SCI) subjects using FES [7]. In FES rehabilitative processes it is important to estimate the efficiency and suitability of prescribed measures which may result in faster walking or a larger step length. We had to meet several specific requirements such as low patient encumbrance and compatibility with a FES stimulator. Our device is an addition, and is used in conjunction with a microprocessor-based stimulator for FES gait synthesis [14] with the objective of integrating electrical stimulation and gait measurement functions. A stand-alone version of the system has been developed for use with a PC compatible computer.

The main requirements for a distance/velocity meter were: low power consumption, small size, accuracy to at least 2%, fixed sampling rate of at least 25 Hz, range of minimum 10 m, reliability, simplicity, microprocessor bus compatibility and applicability to non-laboratory environments where different random environmental disturbances are present.

There are two usual approaches for US-only based measurements. The first principle is a sonar like approach. The moving object emits US pulse bursts. The sound echoes from a fixed plane back to the emitter/receiver. The time elapsed between emission and detection of echo is directly proportional to the absolute distance between the emitter and the reflection plane. This principle is used by bats.

The second principle is only suitable for measuring the relative displacement between the initial and current position of an object and is also echo based. In this case the emitter, placed on the moving object, is generating a continuous US signal. The displacement is obtained by integrating the difference between the source and the echoed signal that occurs due to the Doppler phenomenon. The theoretical sensitivity of the method is half the wavelength (i.e. approximately 3 mm at 50 kHz US source). To obtain the correct result, the US signal from emitter to the reflection plane cannot be interrupted. This may not always be possible in the everyday rehabilitation environment.

Both methods require considerable energy because both emitting and receiving units have to be powered from the same portable source. The emitted US power flux density should be high in order to achieve adequate signal/noise ratio of the echoed signal. This increased US power increases the power consumption.

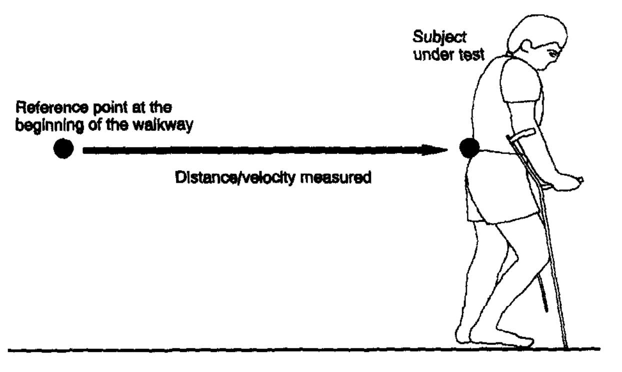

Fig. 1. The idea of the proposed COB movement measuring device: the distance covered and instantaneous velocity is determined with respect to the reference point at the beginning of the walkway.

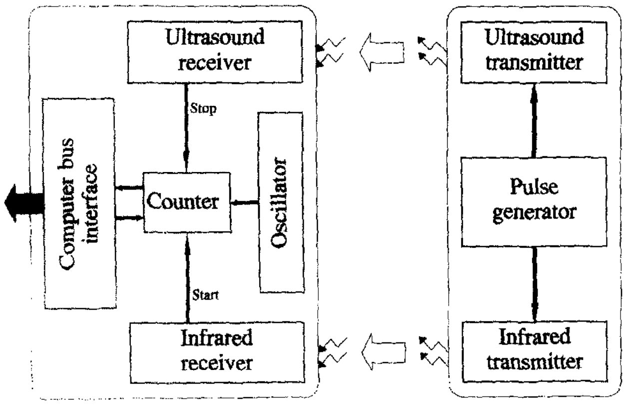

Fig. 2. Principle of the US/IR distance measuring system: The system consists of transmitting and receiving unit. Both transmitters synchronously generate IR and US pulse. When the IR receiver detects the presence of IR light, it resets and starts the counter. The US receiver, triggered by the received US signal, stops the counter. The oscillator pulses are counted during the time the US needs to travel from the transmitter to the receiver.

To overcome the problems of this system we combined infrared light (IR) and US as it is shown in Fig. 2. The system is divided into two physically separated units. One is placed on the moving subject and the second at the reference point at the start of the walkway. The first unit contains both transmitters. The second receiving unit includes both receivers and interface logic, computing the distance to the reference point. Both transmitters synchronously generate IR and US pulses. When the IR receiver detects the presence of IR light, it resets and starts the counter. The US receiver, triggered by the received US signal, stops the counter. The oscillator pulses are counted during the time the US needs to travel from the transmitter to the receiver. By choosing adequate oscillator clock frequency, it is possible to calibrate the system directly in cm or mm. Repetition rate of transmitter IR and US pulse generation determines the system sampling frequency. As the system is measuring the absolute distance between the transmitter and receiver, occasional disruption of IR and US beams does not affect the overall system function: the measurements continue after the signal interrupt and are then valid again.

The distance between the two units is derived in the following way. Both IR and US signals travel the same measured distance s, each with its own velocity as defined in Eq. (1):

$$s = c \cdot t_c \qquad s = v_s \cdot t_s = v_s(t_m + t_c) \tag{1}$$

In Eq. (1): t_s is the actual propagation time of US over the distance s, t_c refers to the actual IR propagation time over the distance s, v_s is the speed of sound, c represents the speed of light and t_m is the measured US propagation time over the distance s.

The counter in the receiving unit is running exactly for t_m. We obtain the exact formula for calculating the measured distance by eliminating the unknown t_c:

$$s = \frac{v_s \cdot t_m}{1 - \frac{v_s}{c}} \tag{2}$$

Since the speed of light is several magnitudes higher than the speed of sound, the fraction in the denominator of Eq. (2) may be neglected as shown in Eq. (3):

$$s = v_s \cdot t_m \tag{3}$$

The derived formula is trivial and was hence hardware implemented as described above. The instantaneous velocity is derived by differentiating the two consequent distance recordings.

Both transmitting and receiving units are made on a single two-layer printed circuit board. Special attention has been paid to the need for low power consumption. The transmitter block scheme is shown in Fig. 3. A NE556 integrated circuit is employed for US and IR pulse-bursts generation. Frequency f_s determines the instrument sampling rate while the f_r determines the US frequency. The logical part is made of HCMOS logic elements. US power amplifier is designed as a class B bridge amplifier. A special differentiating circuit has been designed to properly shape the IR activation signal. Transmitting elements are LED diodes for IR and piezo loudspeakers for US respectively. The transmitting unit requires + 12 V power supply.

The receiving unit employs a single + 5 V power supply. The block scheme of the receiver is shown in Fig. 4. The MAX7660 voltage converter is used for generating a negative − 5 V power supply, required for both amplifiers. A three stage TL071 based amplifier is utilized for amplifying and clipping the received US signal. The IR receiver and amplifier are integrated in a single chip TBA2800, widely used for TV set remote control. A temperature dependent oscillator counterbalances the influence of temperature on US velocity. A three-state output counter/register 74HC590 is used for

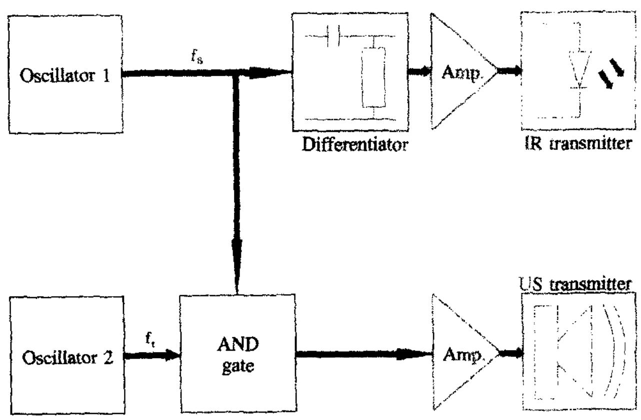

Fig. 3. Transmitter block diagram: Frequency f_s determines the instrument sampling rate and the f_r determines the US frequency. AND gate modulates the continuous US signal with the desired sampling frequency f_s. Differentiaton is used to shorten the transmitted IR pulse signal.

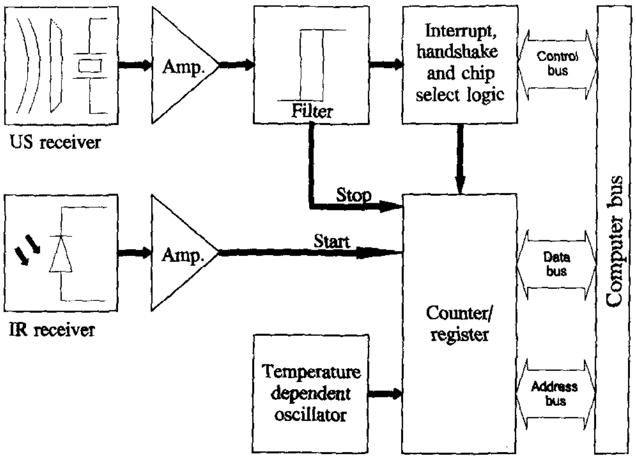

Fig. 4. Receiver block diagram: Amplifiers for both US and IR signal are used to amplify and clip the detected signals. A three-state output counter/register counts the pulses from the temperature dependent oscillator. The counting is initiated by the start signal and terminated by the stop signal. A digital circuit is added to obtain a standard microprocessor bus interface.

converting the measured distance into a digital form. As the distance is measured independently from the host computer, an interrupt based handshaking mechanism is implemented to signal that the measured distance data is ready.

In a stand alone version an additional interface was added to generate suitable digital signals which can be inputted to a standard PC parallel printer port.

The proposed system has several advantages. Either transmitter or receiver unit can be placed on the moving object. If the device is used together with a FES stimulator, only one unit is powered from the stimulator thus expanding battery life. Conventional mains supply is then used for the other unit. Transmitters need to emit less power as compared to the usual methods, since the travelling distance of US signals is equal to the distance measured.

As already mentioned two versions of the ultrasound distance-velocity measuring system have been developed so far. They are both functionally equal; the only difference is in their physical dimensions and the computer interface. The first version uses a microprocessor-based multichannel stimulator as a host computer, while in the second one, referred here as a stand alone version, the IBM/PC is utilized.

In the electrical stimulator based version, the receiving unit with the interface logic, (which is less power demanding as compared to the transmitting unit), is placed approximately at the patient's COB.It is connected to a special stimulator system port [14]. The transmitting unit is placed at the reference point at the start of the walkway. In this way the distance-velocity measuring system is an addition to the microprocessor based multichannel electrical stimulator which also serves as a control and storage unit for the gait measurement data.

In the stand alone version the transmitter is positioned on a tested subject. The receiving unit is placed at the start of the walkway to avoid additional subject cabling. This set-up does not influence the system overall functionality. The instrument output is connected to the standard PC parallel printer port. and the PC continuously record all the distances measured.

Fig. 5 shows a paraplegic subject under test walking with help of FES. The subject is utilizing the walker for upright balance and partial support. The prototype of the stand alone distance/velocity measuring unit was utilized in this case. The unit A is the transmitter box, which is placed approximately at the patient's COB, and is fitted with strips. The unit B is the receiver box, which is placed on the table at the end of the walkway, and is connected to the remote computer.

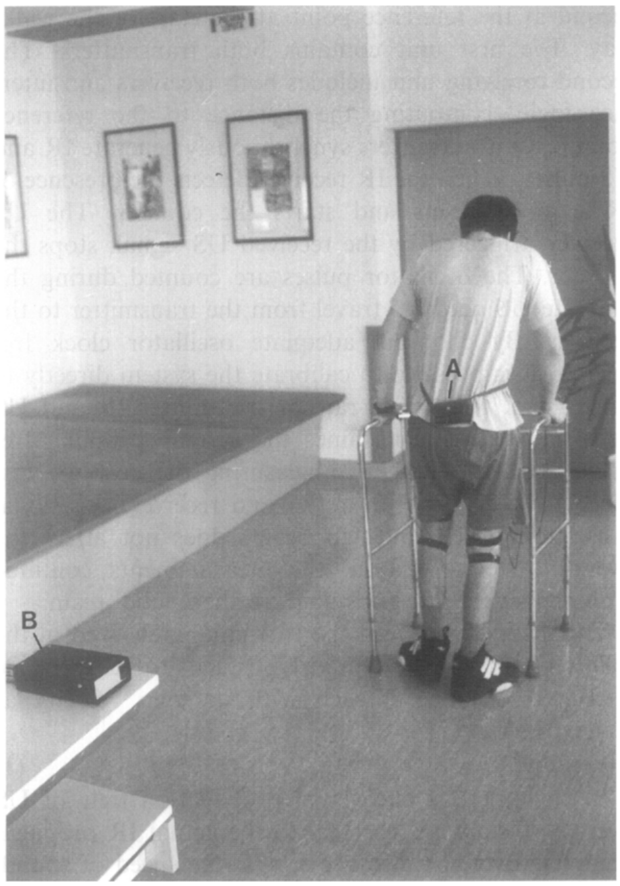

Fig. 5. The complete T-9 paraplegic subject fitted with the distance/velocity measuring device. The subject is walking with the help of 4-channel FES and is utilizing a walker for upright balance and support. The unit A is the transmitter box and the unit B is the receiver box which is connected to a remote computer.

3. Study design

We performed two types of tests to verify the capabilities of the system. The first test was a determination of static accuracy in the laboratory environment. As gait is a dynamic process two types of gait were recorded. The first one was of normal gait. This enabled us to validate the distance/velocity measuring system by comparing the results with well known data [3]. The second recorded gait type was the paraplegic FES assisted gait, which is inherently inferior compared to the normal one. His walk was clearly abnormal. We can consider normal and FES assisted gait as two extremes with most other pathological gaits in a spectrum between.

All recorded gait data was obtained for a free gait on hard and level surface. The gait data was acquired on males. The paraplegic had a complete lesion at T-12 level and was considered an averagely experienced FES walker. (In selected spinal cord injured patients the restoration of reciprocal bipedal gait can be realized by means of functional electrical stimulation FES) [7]. This patient was using 4-channel FES also known as 'minimal walking pattern'. Swing phase was realized through afferent FES, provoking a flexion reflex resulting in simultaneous flexion of hip and knee and ankle dorsiflexion and thus providing clearance of the foot from the ground. Stance phase was achieved by stimulating bilaterally the knee extensors enabling sufficient support to the patient. He also utilized crutches for balance and partial support. The patient utilized a statically stable walking pattern known as 'crawl gait' which offers superior stability properties.

Results shown Figs. 6 and 7 were obtained using the stand alone system connected to the PC. The transmitter unit was placed on the lower back approximately at the tested subject's COB height. The setup was similar to that shown in Fig. 5. During the measurement only the distance data were recorded whilst both velocity and acceleration were calculated off line. The gait velocity was derived by differentiating two consequent distance recordings. The gait acceleration is derived from the velocity in the same way. Smoothing the data after each differentiation is achieved by applying a digital fifth order moving average filter.

The signals from foot switches were recorded simultaneously with the distance recordings to detect gait phases. Foot switches used were tape switches from MIE Medical research. Signals from foot switches were sampled with an A/D converter which is in our case a Burr-Brown PCI20098C-2 Multifunction I/O board.

4. Results

The distance/velocity meter resolution achieved was 1 mm and the sampling rate was set at 25 Hz. The accuracy achieved was just above 0.5% in the laboratory environment within a 10 m range. This is demonstrated in Table 1 presenting the results of an accuracy test. This system was tested manually under static conditions in a laboratory environment with stable atmospheric conditions. The accuracy was significantly worse when measured dynamically or in a non-laboratory environment due to uncompensated atmospheric influences. However, the accuracy remained within 2% even in the worst case situation.

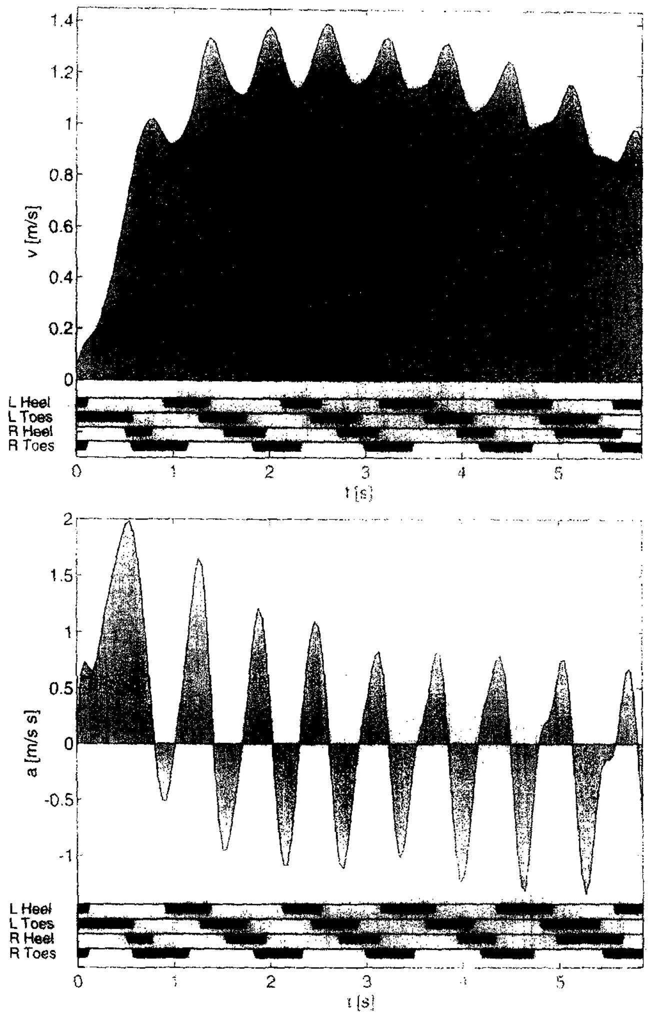

Fig. 6. COB velocity and acceleration with basograms assessed in a healthy person.

Fig. 6 shows typical records for the healthy subject. The curves presented are velocity and acceleration of the COB versus time. Basograms are included with both curves. The velocity curve demonstrates the well known phenomenon of a sinusoidal ripple during stationary gait which indicates the energy efficiency of a healthy subject in the gait cycle.

The results produced in the complete T-12 paraplegic subject are shown in Fig. 7. The velocity and acceleration curves significantly differ from those measured in

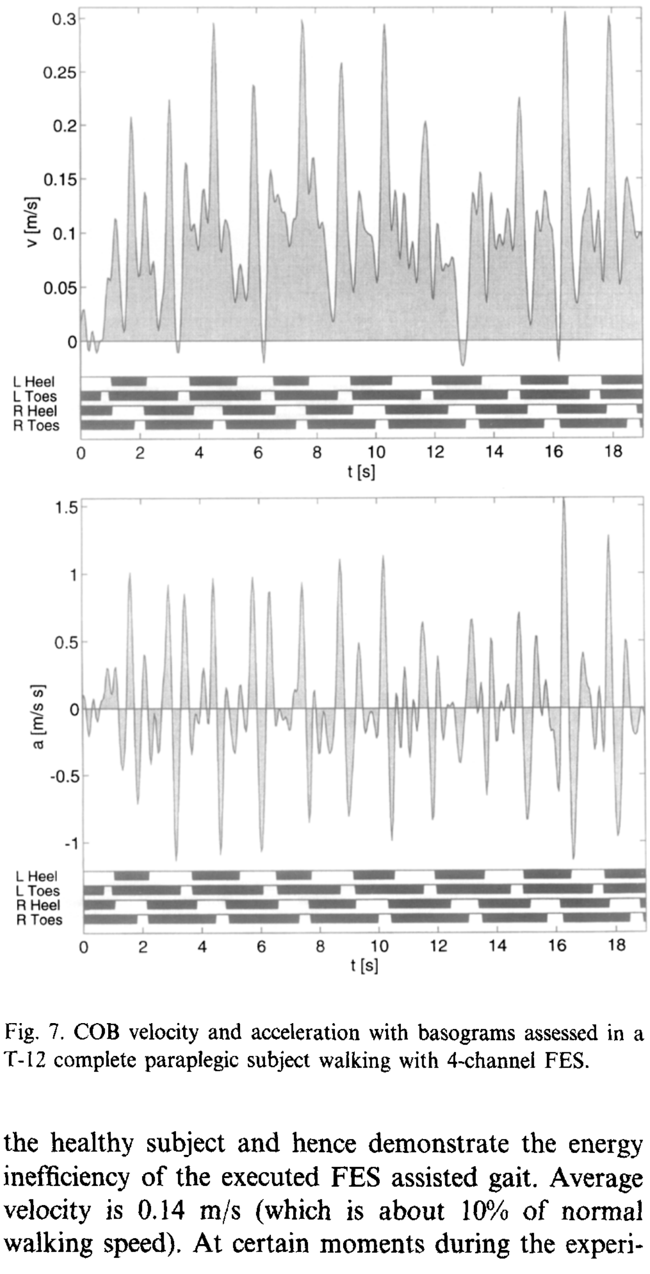

Fig. 7. COB velocity and acceleration with basograms assessed in a T-12 complete paraplegic subject walking with 4-channel FES.

the healthy subject and hence demonstrate the energy inefficiency of the executed FES assisted gait. Average velocity is 0.14 m/s (which is about 10% of normal walking speed). At certain moments during the experiment the COB is even moving posteriorly, which is nearly impossible to record with string based methods. A paraplegic subject performs the translation of the COB in the direction of walking with the help of his preserved or intact trunk muscles acting through the walking aid. This results in a strong forward-backward movement of the pelvis. This affects the COB movement as the COB is a 'fixed point' close to the pelvis. Therefore, the COB movement measured in this way differs from the actual COG movement, yet it still has significant comparative value.

Table 1
Distance/velocity meter accuracy test

Reference distance (m)	Measured distance (m)		Error (±%)
	Min	Max	
1	0.998	1.003	0.30
2	1.998	2.002	0.10
3	2.999	3.002	0.07
4	3.998	4.004	0.10
5	5.003	5.007	0.14
6	6.006	6.009	0.15
7	7.007	7.012	0.17
8	8.013	8.021	0.26
9	9.016	9.024	0.27
10	10.044	10.052	0.52

5. Discussion

From a technical point of view the distance/velocity measuring system we used was sufficiently reliable and fulfilled our initial requirements. Occasionally, the measurement process was malfunctioning because of rather small transducer reception/radiation angles. This was particularly true for the US transducers. When the transmitter was rotated more than about 30° from the moving patient and receiver, it did not emit enough energy and thus disabled the signal detection. The same was true for the receiving unit. Small rotation of the transducers around the roll and pitch angles could introduce small errors, as the transducers do not have ideal phase characteristics [15]. This type of error could have been lessened if transducers with wider receiving/transmitting angles and/or better phase characteristics had been used.

The systematic errors which resulted in an inaccuracy of the measuring system originated mainly from atmospheric conditions. These conditions influenced speed of sound (e.g. temperature, pressure, humidity, etc). We utilized a temperature compensated design because temperature was the most influential parameter. Another error source was in the geometric setup which affects the string based methods in the same way. The Doppler phenomenon also became important at higher speeds. The above mentioned errors can be compensated either through hardware or software alterations. However there were still some effects that we could not compensate for, e.g. temperature gradient along the measured distance, air jets and streams, etc.

The distance velocity meter can to some extent be adapted to specific tasks. For example, the sampling rate can be increased at the expense of decreased range. If some kind of identification in the form of modulated signals is added to the transmitted signals, then even multiple transmitters can be traced.

From the clinical point of view the most important goal was obtaining a simple, portable and reliable gait evaluation system, which can be used in non-laboratory environments. It is our experience that sophisticated gait analysis systems cannot be used in everyday clinical work because they are too cumbersome, too expensive or are even unavailable. Such systems require special facilities and personnel to operate them. Our distance/velocity meter can be utilized by technically untrained personnel like physical therapists or medical doctors and in addition, the subject is ready for a measurement within seconds.

Therefore, the described system can easily be used and is reliable enough to detect small changes in gait velocity in the different phases of walking. Small changes are often very important in the rehabilitation process as they indicate the usefulness of the prescribed measures and/or rehabilitative aids. (This is particularly true for the FES rehabilitation of SCI subjects where fast detection of small changes in gait can lead to the improvement of FES stimulation patterns and hence improved gait). Large differences in gait performance that are obvious, e.g. normal versus FES assisted gait, can be objectively and quantitatively evaluated.

Although the distance/velocity meter described in this article was originally designed as an addition to FES gait rehabilitation, it has proved to be useful in other more general analyses. It can, together with other transducers, serve as an inexpensive and simple portable gait evaluation system. The proposed distance/velocity meter may also serve as an improved sensor for developing simple and small new generation gait computers in such a format that clinicians and physical therapists could carry them like pocket calculators.

Acknowledgements

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References

[1] Perry J, Bontrager EL, Bogey RA, Gronley JK, Barnes LA. The Rancho EMG analyzer: a computerized system for gait analysis. J Biomed Eng 1993;15:487–96.

[2] Kralj A. Instantaneous progression velocity, its importance and relation to other gait data. Digest 11th International conference on medical and biological engineering Ottawa. 1976;576–577.

[3] Winter DA. Biomechanics of Human Movement. New York: Wiley, 1979.

[4] Aiello L, Dean C. An Introduction to Human Evolutionary Anatomy. London: Academic Press, 1990.

[5] Bajd T, Kralj A. Simple kinematic gait measurements. J Biomed Eng 1980;2:129–32.

[6] Nakamura T, Yamamoto Y, Yamamoto T, Tsuji H. Distance and velocity meter for human motion analysis. Med Biol Eng Comput 1994;32:115–8.

[7] Kralj A, Bajd T. Functional Electrical Stimulation: Standing and Walking after Spinal Cord Injury. Boca Raton, Florida: CRC Press, 1989.

[8] Karčnik T, Kralj A, Munih M. Ultrasound distance-velocity measurement incorporated into FES rehabilitative system. Proc 4th Int Workshop Electro-stimulation Vienna, 1992:48–51.

[9] Jare M, Bajd T, Kralj A. Simple Approach to Assessment of Human Gait Efficiency. Proc 13th Annual Int Conf IEEE EBMS Orlando, 1991;615–616.

[10] Reswick J, Perry J, Antonelli D, Su N, Freeborn C. Preliminary evaluation of the vertical acceleration gait analyzer. Proc 6th Int Symposium on External Control of Human Extremities Dubrovnik, 1978;305–314.

[11] Bajd T, Kljajič M, Trnkoczy A, Stanic U. Electrogoniometric measurement of step length. Scand J Rehab Med 1974;6:78–80.

[12] Lindstedt G, Olsson G. Using Ultrasonics for Sensing in a Robotic Environment. Proc IEEE Conf Rob Automat Altanta, 1993;671–675.

[13] Suga N. Biosonar and Neural Computation in Bats. Sci Am 1990;262:34–9.

[14] Karčnik T. Mikroračunalniški stimulator z merilnimi in diagnostičnimi funkcijami. M.S. Thesis, Ljubljana: FER, 1993.

[15] Parrilla M, Anaya JJ, Fritsch C. Digital signal processing techniques for high accuracy ultrasonic range measurements. IEEE Trans Instr Meas 1991:40:759–63.