Estimation of Speed and Incline of Walking Using Neural Network

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***Abstract*—A portable data logger is designed to record body accelerations during human walking. Five subjects walk first on a treadmill at various speeds on the level, and at positive and negative inclines. Then, the subjects performed a self-pace walking on an outdoor test circuit involving roads of various inclines. The recorded signals are parameterized, and the pattern of walking at each gait cycle is found. These patterns are presented to two neural networks which estimate the incline and the speed of walking. The results show a good estimation of the incline and the speed for all of the subjects. The correlation between predicted and actual inclines is $r = 0.98$, and the maximum of speed-predicted error is 16%. To the best of our knowledge these results constitute the first speed and incline estimation of level and slope-unconstrained walking.**

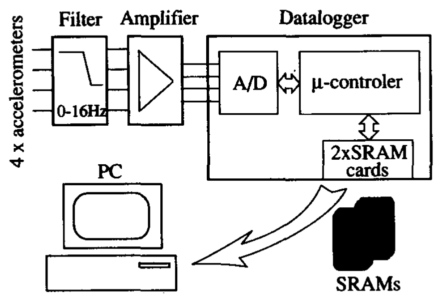

Fig. 1. Block diagram of the measuring system.

I. Introduction

THE energy cost of human walking when the body weight is known can be calculated if the speed and the incline of terrain are known [1]. Most of the studies concerning human energy expenditure are performed in an exercise laboratory where the slope and the speed of walking are imposed by the treadmill. Nevertheless, in overground walking, these two parameters must be determined in order to accurately assess the level of physical activity.

Accelerometry [2]–[4] constitutes a promising technique for detecting the movement of the body and estimating the energy expenditure. In this paper it is applied to determine the patterns of different types of walking at various speeds of movement and various inclines of the terrain. A new method for parameterizing the body acceleration signals is introduced. These parameters constitute the pattern of walking and are presented to two neural networks which estimate the incline and the speed of walking.

II. Measuring System

Movements in all three dimensions need to be recorded for the successful identification of human walking. Three piezoresistive accelerometers (IC Sensors 3021) oriented in orthogonal directions, placed in a waist belt and located on the back, measure the forward, vertical, and heel accelerations of the trunk as the subject walks. A fourth accelerometer fixed on the top of the right heel measures the heel forward acceleration during walking. A portable data logger is designed to record the acceleration signals. It has an autonomy of 24 h and a memory capacity up to 16 Mbytes, which is quite enough for one daily physical activity recording. The data logger is lightweight (less than 500 g) and is fixed on the subject's waist belt. All of the 4 acceleration signals are amplified, calibrated, low-pass filtered (0–16 Hz), digitized (12 bit) at 40 Hz and stored on a 2 Mbytes static RAM (SRAM) memory card (see Fig. 1). At the end of the recording the data in the memory card is transferred to a personal computer for further analysis.

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III. Experimental Design

Five volunteer healthy subjects (two males, three females, age 21 ± 2 years, height 175 ± 10 cm, weight 64 ± 6 kg) walked on a treadmill at their own preferred speed on the level, and at, respectively, positive and negative inclines of +5, +10, +15, −5, −10, −15%. The experiments were repeated with the subjects walking under and over their own preferred speed on the level and at +10%, −10% incline. The speeds of walking ranged between 3.5 and 7 km/h according to subjects and inclines. The duration of each experiment was 1 min. Fifteen types of different walking are performed: 3 of level, 6 of uphill and 6 of downhill walking. The total period of treadmill walking is 15 min. After each treadmill walking, the subjects performed a self-paced walk on an outdoor test circuit involving 4 roads of various inclines. Road 1 is 422 m flat ground, road 2 is a 444 m of ±7% incline, road 3 is 124 m of ±16.9% incline and road 4 is a gradual incline, from −4.9 to 4.2%. Each inclined road (road 2 to 4) was covered twice in opposite directions (downhill and uphill). This walking trial took between 25 and 35 minutes depending on the subject's walking pace and fitness. The subjects were allowed a recovery period of approximately 1 minute at the end of each road along the track.

IV. Parameterization of Body Accelerations

Many parameters such as effective value of the vertical body accelerations, step length, forward velocity change in each step, and stride time are correlated to walking speed [5]–[7]. But these correlations can be varied according to subjects and the range of speed. Relatively few authors have studied the correlation between gait parameters and the incline of the terrain.

In this work the following parameterization based both on physiological and statistical aspects of body accelerations is introduced. First, the negative peaks of the right heel acceleration are found. These peaks correspond to the heel strikes and are used to segment the four recorded signals. Then the gait cycle (2 strides) is computed as the time between two heel strikes. Finally, for each cycle a pattern of 10 parameters is found: median values of forward, vertical and lateral accelerations, variances of the forward and vertical accelerations, covariances between the heel acceleration and each of the frontal, vertical and lateral accelerations, peak of the heel deceleration and the time corresponding to the gait cycle.

The training acceleration recorded on the treadmill is parameterized to form a set of 360 training patterns. The first third corresponds to 40 $\times$ 3 gait cycles on the level at 3 speeds, the second third to 20 $\times$ 6 gait cycles of 6 types of uphill walking and the last third to 20 $\times$ 6 gait cycles of 6 types of downhill walking. In order to show the significance of the chosen parameters in our analysis of walking, for each one of the 15 types of walking the 10 parameters are averaged over the number of gait cycles, and their respective correlations with the inclines (respectively the speeds) corresponding to these 15 types of walking are calculated. This analysis shows that the variation of each parameter with speed and incline is mainly nonlinear and that these parameters are correlated with different degrees to incline and speed. The correlations vary also according to different subjects. It appears that for all of the subjects, the median values of forward acceleration and the covariance between the heel acceleration and each of the vertical and the lateral accelerations are strongly correlated with the incline, whereas the variances of the vertical acceleration and the time corresponding to the gait cycle are strongly correlated with speed. For the rest of the parameters the correlation to speed or incline rather depends on each subject's manner of walking. All of the 10 parameters have been considered because of the varied nature of walking of each subject.

V. Neural Network Structures

Serious progress in ANN research has been made in the past decade mainly in pattern recognition [8], whereas its application to gait analysis is very new [9]–[11]. In a previous work, we have presented the feasibility of identification and dissociation of level and slope walking based on a Kohonen ANN [9]. Although the Kohonen ANN provided some information on the magnitude of the incline and the speed, this was not sufficient for an accurate assessment of these two parameters of walking.

In this work two ANN's of two-layer perceptrons are designed. The output of the first ANN corresponds to incline and that of the second ANN to speed of walking. Each ANN consists of 10 input units, a hidden layer of 5 units and an output layer of one unit.

Each component p_{ni} of the input pattern P_i is connected to each unit j of the hidden layer through a weight w_{jn} and a bias b_j. The output from each hidden-layer unit y_{ji} is given by the following nonlinear function

$$y_{ji} = \tanh\,(x_{ji} + b_j) \tag{1}$$

where $x_{ji} = \sum_{n=1}^{10} w_{jn} \cdot p_{ni}$ is the weighted input of the hidden unit j; tanh is the tangent hyperbolic function.

Each unit of the hidden layer is connected to the output through a weight v_j. The output O_i of the network is

$$O_i = \sum_{j=1}^{5} v_j \cdot y_{ji} + c \tag{2}$$

where c is the bias of the output unit.

The learning rule to adjust the weights and biases of the networks is based on the back-propagation training algorithm [12]. However, three modifications were added to this rule. First, to decrease the training time, the Nguyen–Widrow method was used for initialization of the weights of the network [13]. Secondly, instead of updating the network weights after each pattern presentation, the network was updated only after the entire set of the patterns to be learned had been presented to the network. Thirdly, the learning rate varied dynamically so that the algorithm utilizes an adaptive learning rate, as determined by the local optimization topography [14]. A pair of networks (one for incline and one for speed estimation) is designed for each subject. Each ANN requires a training and a prediction phase. First the weights are initialized, then the set of 360 training patterns and the corresponding desired outputs T_i (incline for the first ANN and speed for the second ANN) are presented to the networks. The output of the networks, O_i, is determined. The weights and the biases of the networks are then adjusted so as to minimize the sum squared error $\Sigma(T_i - O_i)^2$ of each network. This was done continuously by changing the values of the weights and biases in the direction of the steepest descent with respect to the error until the weights converged and the sum squared error was reduced to a specified tolerance. At the end of the training phase the weights and biases will be frozen and the classification phase can be started. Unknown patterns are presented to the network's input, incline and speed estimation are carried out.

VI. Results

The recorded accelerations are parameterized and the patterns corresponding to the gait cycles are determined. The ANN's are trained first by the patterns obtained during treadmill walking (training phase). Then the patterns of overground walking are presented to the ANN's for incline and speed estimation (classification phase). Fig. 2 shows a typical result (for a female subject). It can be seen that (Fig. 2(a)) there is

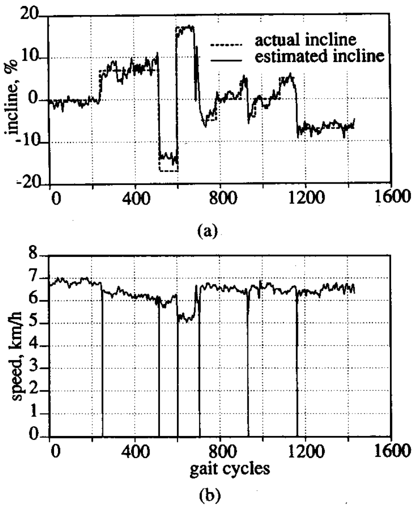

Fig. 2. (a) Typical incline and (b) Speed estimation for a female subject walking on the test circuit. The actual incline is also presented in (a) for comparison. The interrupted speeds correspond to the subjects being at rest.

a relatively small deviation of the estimated incline from the expected incline. For each subject the inclines predicted by ANN are determined and plotted against the actual inclines of the test circuit (Fig. 3). There is close agreement between predicted and actual inclines since a strong relationship ($r = 0.98$) is found. The standard deviation of the estimated incline is less than 2.3%.

In order to test the accuracy of the speed estimation, the distance covered for each part of the test circuit is determined by integrating the estimated speed over the corresponding time and is compared to the actual length of each part of the test circuit. The estimated covered distance for each part and for each subject and the expected length are presented in the Table I. Using the Student t distribution ($n = 5$), and a 90% confidence intervals, the error of estimated covered distance in respect to the expected length are reported in Table I. It can be seen that this error is less than 16% in the worst case (at $\pm 16\%$ graded walking). This error can be considered also as the mean error of speed estimation.

VII. Conclusion

A portable data logger which allows body accelerations to be recorded is designed. A new method for the parameterization of body accelerations during walking is proposed. Based on this method the incline and the speed of walking are estimated using neural networks. The networks are trained independently for each subject, so the results obtained take into account each subjects style of walking. An alternative technique to detect the up/down motion and assess the incline of terrain consists of using an altimeter. Unfortunately available miniature sensors exhibit limited resolution (few dozen of centimeters) and high sensitivity to external parameters such as temperature and local pressure variations (sun, shadow, wind). The present method has the advantage to estimate the incline at each gait cycle without being perturbed by the atmospheric variations.

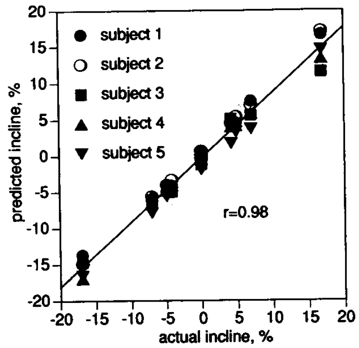

Fig. 3. Relationship between predicted inclines obtained from ANN and actual inclines of the test circuit.

TABLE I

Comparison of the Estimated Covered Distance (μ_{est}) and the Expected Distance (μ_{exp}) for Different Subjects and Different Road of the Test Circuit. Error is the Relative Error at 90% Confidence Interval. All Values are in Meters Except Error in Percentage

	road 1	road 2		road 3		road 4	
	flat	uphill	downhill	uphill	downhill	on the way	way back
subject 1	455	465	458	120	129	405	405
subject 2	402	411	398	116	107	392	391
subject 3	423	435	448	131	117	401	401
subject 4	423	474	440	122	112	407	411
subject 5	414	441	436	135	114	406	407
μ_{est}	423	445	436	125	116	402	403
μ_{exp}	422	444	444	124	124	408	408
Error,%	11	13	11	15	16	3	4

A good agreement between actual and predicted value has been found. However the accuracy of the prediction depends upon: 1—the difference between treadmill and overground walking, 2—a sufficient number of patterns to include speed and incline fluctuations that may be encountered during overground walking. Training the ANN's with a large number of speeds and inclines, will certainly make the method more powerful and more accurate, but it will increase the training time.

The most important and original aspect of this study is the ability to predict the incline and the speed of overground walking from data collected during treadmill walking. Since the energy expenditure is directly related to the speed of walking and the incline of terrain, the proposed method will provide a useful tool for objectively and accurately measuring the daily physical activity of human subjects.

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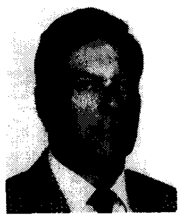

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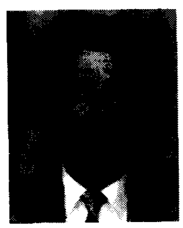

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