Journal of Electromyography and Kinesiology 9 (1999) 149–157

Cost of walking and locomotor impairment

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Abstract

The aim of the present study was to evaluate the importance and the necessity of metabolic measurements to quantify locomotor impairment in a clinical context. Oxygen consumption, heart rate, pulmonary ventilation and walking speed were measured during locomotion in 14 normal subjects, used as a control group, and 82 patients with different pathologies [hemiparetic, paraparetic, tetraparetic, orthopaedic and paraplegic patients, who walked using a reciprocating gait orthosis (RGO)]. The subjects were characterized on the basis of a cumulative impairment score (CIS), based on clinical scales commonly used to evaluate impairment and disability in locomotion. Appropriate indices of energy, cardiac and ventilatory costs expressed per metre walked, globally called physiological costs, were obtained. It resulted that the most comfortable speed (MCS) of normal subjects was significantly higher than that of each group of patients. Normal subjects' physiological costs were found to be significantly lower than those of patients who needed either a device or the help of a person to walk. All measured parameters correlated significantly with each other. The MCS was found to be the most correlated parameter with the CIS ($r = 0.8$), and therefore it must be considered the best single measurement, if only one is to be used. Measurements more precise than MCS, such as the physiological costs, may be necessary in clinical trials.

Keywords: Human locomotion; Energy cost; Cardiac cost; Impairment assessment

1. Introduction

The need for a simple method to estimate walking impairment in the clinical setting has been frequently stressed [1,2]. Many authors [3–9] suggest that the metabolic energy cost of walking increases in patients with locomotor impairment. Olgiati et al. [2] suggest that this is a result of spastic co-contraction of agonist–antagonist muscles and of an inefficiency of body kinematics which results in a waste of mechanical energy. Furthermore, some suggest that the greater cost is also due to a reduced natural walking speed, because generally disabled people adopt a very slow walking speed [9,10]. Indeed, normal walking has the minimum cost at the normal natural speed, which is the speed the normal subject spontaneously adopts (about 1.3 m s^{-1}). Below and above this speed the cost increases [11,12].

It has been assumed that the change in heart rate per unit of distance is a good indicator of the energy cost [13]. Measuring the heart rate (HR) is more easily done than measuring metabolic energy cost, which requires the measurement of oxygen intake ($\dot{V}_{O_2}$).

An increase in breathing rate and volume, in addition to an increase in heart rate, is often seen during ambulation in disabled patients. This is also presumed to be the result of the greater energy cost of ambulation [7].

The purpose of this study is to address a number of the questions raised above. First, we wanted to establish how reliable the metabolic energy cost is as an indicator of the walking impairment in patients suffering from neurological or orthopedic diseases. Second, we wanted to determine whether the heart rate per unit of distance could be a good substitute for the metabolic energy cost. Third, we wanted to test the walking speed, because the

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1050-6411/99/$ - see front matter
PII: S1050-6411(98)00046-7

speed adopted by impaired patients is much slower than that of normal subjects [1,6,8] and, therefore we wanted to test whether the walking speed could be used by itself as an indicator of walking impairment. Our hypothesis, however, is that both physiological costs (such as energy cost, ventilatory cost and cardiac cost) and walking speed are important measures in a clinical setting; i.e., we hypothesize that the use of a single parameter only could sometimes be misleading.

2. Materials and methods

Ninety-six subjects (14 normal controls and 82 disabled patients) participated in this study (see Table 1). Informed consent was obtained, and the patients, selected from a rehabilitation center, were assessed clinically and studied in a locomotion laboratory.

The patients were divided into five groups on the basis of their diagnosis. Group A consisted of 31 hemiparetic patients (23 cerebral stroke, three neural tumor and five trauma). Group B consisted of 21 paraparetic patients (five tumor, three infectious disease, five trauma, seven herniation of nucleous pulposus, one multiple sclerosis). Group C consisted of six tetraparetic patients (three trauma, one infectious disease, one hydrocephaly, one spondylarthrosis). Groups A, B and C had partial voluntary control of leg muscles. Group D consisted of 13 orthopedic patients with partial walking impairment (nine femoral fractures, one hip fracture, one arthrosis of the knee, one total knee replacement, one total hip arthroplasty). The patients of this group were tested about one year after surgery with the exception of a patient with severe knee arthrosis who had had no surgery. However, this subject had been showing a pathological locomotion pattern due to pain for nine months prior to the test. Group E consisted of 11 paraplegic subjects, with complete lesions of the spinal cord (ASIA A). These patients had been rehabilitated to stand and walk by means of an external orthosis, the Reciprocating Gait Orthosis (RGO) [14]. Group F was composed of normal subjects.

The level of locomotor disability of each patient was assessed by summing the partial scores of two scales commonly used in clinics (the Canadian Scale [15] and the Barthel index [16]) [17]. In detail, we used two items of the Canadian neurological scale, to measure the proximal and the distal strength of the most impaired lower extremity (three-point scale). The reliability of each item had also been validated separately [15]. Based on the Barthel index [16], we measured the autonomy in walking 45 m and in climbing stairs, and scored it up to 25 points. In order to have a maximum normalized value equal to 1, we normalized the score obtained by each subject in each scale with respect to the maximum value. The two normalized values were then summed, in order to obtain a cumulative impairment score (CIS) [16]. In this way, the maximum CIS value was equal to 2. In the present study, normal subjects (group F) included symptom-free subjects with a CIS equal to 2.

All subjects were requested to walk up and down a 20 m long pathway. Patients were asked to walk at their most comfortable speed (MCS). Previous work demonstrated that patients with locomotor impairment have difficulty changing speed and will choose the MCS [17]. Normal subjects, however, were requested to walk at three self-selected speeds: normal (MCS), fast and slow speeds. Five of them performed a further test walking at a very slow speed. The slow and the very slow speeds were closer to the patients' MCS and were used to determine whether they could serve as controls.

In each subject $\dot{V}_{O_2}$, HR and pulmonary expiratory ventilation ($\dot{V}_E$) were measured, at rest and during walking, by means of a telemetric device (K2 Cosmed, Italy). All tests of patients were performed at the same time of day, in the morning, and under the same conditions (at least two hours after breakfast). Each subject was requested to walk for at least five minutes in order to

Table 1
Anthropometric characteristics of subjects. The patients, with the exclusion of RGO patients, were further classified as independent walkers (IW) and dependent walkers (DW)

Subject group	Sex	No. of subjects	Age (yr)	Stature (m)	Mass (kg)	IW/DW
A (hemiparetic patients)	M	20	60 ± 18	1.74 ± 0.09	71 ± 11	10/10
	F	11	53 ± 16	1.61 ± 0.04	68 ± 14	4/7
B (paraparetic patients)	M	11	42 ± 20	1.73 ± 0.07	68 ± 11	2/9
	F	10	51 ± 22	1.62 ± 0.06	63 ± 9	2/8
C (tetraparetic patients)	M	4	28 ± 9	1.77 ± 0.1	64 ± 6	2/2
	F	2	45 ± 27	1.60 ± 0.08	73 ± 20	0/2
D (orthopedic patients)	M	4	27 ± 4	1.78 ± 0.07	86 ± 32	0/4
	F	9	56 ± 19	1.60 ± 0.05	60 ± 7	5/4
E (RGO paraplegic patients)	M	5	24 ± 4	1.76 ± 0.08	69 ± 11	
	F	6	36 ± 9	1.62 ± 0.04	55 ± 7	
F (normal subjects)	M	12	39 ± 14	1.76 ± 0.05	76 ± 8	
	F	7	36 ± 13	1.58 ± 0.05	62 ± 10	

reach steady-state conditions. The K2 apparatus gave $\dot{V}_{O_2}$, $\dot{V}_E$ and HR data every 30 s. The records obtained during the two final minutes were assumed to be the steady state. The mean value of those two minutes was used.

The walking speed was obtained by dividing the walking distance (m) by the time taken to cover it (s). The overall walking energy cost (WEC) was calculated, following Zamparo et al. [9], as the amount of oxygen consumed per kg body mass per unit distance (expressed in J kg^{-1} m^{-1}). The following formula was used: $WEC = E_W/S$, where E_W is the energy intake during walking in J min^{-1} and S is the speed in m min^{-1}.

The overall walking ventilatory cost (WVC) was calculated as the amount of expired air per kg body mass per unit distance (ml kg^{-1} m^{-1}) according to the following formula: $WVC = \dot{V}_{E_W}/S$, where $\dot{V}_{E_W}$ is the expired air during walking in ml kg^{-1} min^{-1} and S is the speed in m min^{-1}.

The overall walking cardiac cost (WCC) was calculated as the number of heart beats per unit distance (beats m^{-1}) according to the following formula: $WCC = HR_W/S$, where HR_W is the HR during walking in beats min^{-1} and S is the speed in m min^{-1}. WEC, WVC and WCC will be cumulatively called physiological costs.

Second-order polynomial regression curves were calculated for normal subjects to fit WEC, WVC and WCC versus walking speed. Prediction intervals (0.95) were calculated [18] and respective curves were superimposed on the graph. The physiological costs of each patient were also plotted on the graph.

Any possible linear regression analysis was performed between MCS, WEC, WVC, WCC and CIS. A multiple correlation table was built, giving the value of the correlation coefficient (r) of each possible linear regression curve.

One-way ANOVA with a post hoc student-Neuman–Keuls multiple range test was used to compare the difference in CIS, each physiological cost and MCS among the various groups. A further ANOVA and post hoc test was performed by grouping the patients as dependent and independent walkers (IW). We considered dependent walkers (DW) those patients who either used a device such as canes, crutches and walkers or needed the assistance of one or more people. Table 1 shows the number of these patients for each group of pathology. Group E was considered a separate group. In both analyses, group F was used as the control group.

3. Results

In Table 2 the descriptive statistics of each group of subjects is shown. For each parameter considered (MCS, WEC, WCC, WVC and CIS), the mean values and the standard deviations are presented.

In Fig. 1 the mean values of the steady-state WEC, WVC and WCC measurement of each subject are plotted as a function of walking speed. For the normal subjects, who walked at different speeds, the values at each speed were plotted. For each physiological cost, these values were used to build a second-order regression curve (continuous line) with its prediction interval (dotted lines). The following should be noted. Globally taking into account all the physiological costs, 44% of the patients, that is all the RGO subjects (group E) and 25 people of the remaining 71 patients, had physiological costs above the prediction interval of normal subjects. This means that the majority of data measured in patients does not differ from the data obtained in normal subjects required to walk at the same speed as patients. In general, the lower the MCS of the patients, the greater their WEC, WVC and WCC. That is, the subjects who spontaneously selected a very slow walking speed included practically all of the patients with a physiological cost above the upper limit of the prediction interval.

Table 3 shows the correlation coefficients of the multiple linear regression analysis between MCS, WEC, WCC, WVC and CIS. This analysis was performed using the individual data of the subjects of each group. All the correlation coefficients were statistically significant (for 96 subjects and for a P value equal to 0.05, r must be equal to 0.17). The highest correlation coefficient was found between CIS and MCS ($r = 0.8$). When the same analysis was performed excluding normal subjects and RGO patients, (for 71 patients, and for $P = 0.05$, $r = 0.195$), as shown in Table 4, all of the correlation coefficients were still highly significant but the correlation coefficients between MCS and each physiological cost increased relatively with respect to the correlation coefficients between MCS and CIS. The latter demonstrates that the correlation between MCS and physiological costs is stronger than the correlation between MCS and the CIS. In both kinds of evaluation, whether including RGO and normal subjects or not, all of the physiological costs were very highly correlated with one another (the r range was between 0.92 and 0.96).

On the basis of the ANOVA evaluation (Table 5), we found statistical differences in the MCS among groups. The further analysis performed using the post hoc student-Neuman–Keuls multiple range test showed that both group E (MCS mean value equal to 0.17 ± 0.08 m s^{-1}) and group F (MCS mean value equal to 1.28 ± 0.17 m s^{-1}) differed from all other groups. Furthermore, there was a difference between groups B (0.46 ± 0.27 m s^{-1}) and D (0.71 ± 0.26 m s^{-1}). The statistical evaluation for WEC, WVC and WCC did not show any significant difference between groups with the exception of the RGO group, which was found to be significantly different from all other groups. In fact, as also shown in Table 2 (see large standard deviations), individual values were

Table 2
Walking energy cost (WEC), walking cardiac cost (WCC) and walking ventilatory cost (WVC) at the most comfortable speed (MCS), in different groups of subjects

Subject group	No. of subjects	MCS ($m\ s^{-1}$)	WEC ($J\ kg^{-1}\ m^{-1}$)	WCC (beats m^{-1})	WVC ($ml\ kg^{-1}\ m^{-1}$)	CIS
A (hemiparetic patients)	31	0.54 ± 0.26	6.8 ± 3.76	3.86 ± 2.05	11.4 ± 6.2	1.37 ± 0.23
B (paraparetic patients)	21	0.46 ± 0.27	9.3 ± 5.8	5.5 ± 4.4	16 ± 10.38	1.2 ± 0.19
C (tetraparetic patients)	6	0.58 ± 0.41	8.1 ± 4.04	4.7 ± 2.26	12.2 ± 5.65	1.24 ± 0.36
D (orthopedic patients)	13	0.71 ± 0.26	5.45 ± 1.9	3.01 ± 1.32	9.13 ± 3.7	1.47 ± 0.22
E (RGO paraplegic patients)	11	0.17 ± 0.08	27.2 ± 9.9	17.67 ± 9.4	47 ± 19.52	0.4
F (normal subjects)	18					2
Normal speed		1.28 ± 0.17	3.53 ± 0.46	1.47 ± 0.26	4.55 ± 0.56	
Fast speed		1.7 ± 0.23	2.83 ± 0.53	0.38 ± 0.2	3.44 ± 1.06	
Slow speed		0.72 ± 0.15	2.37 ± 0.75	0.18 ± 0.2	2.63 ± 0.85	
Very slow speed		0.24 ± 0.05	3.76 ± 1.5	0.26 ± 0.12	4 ± 1.4	

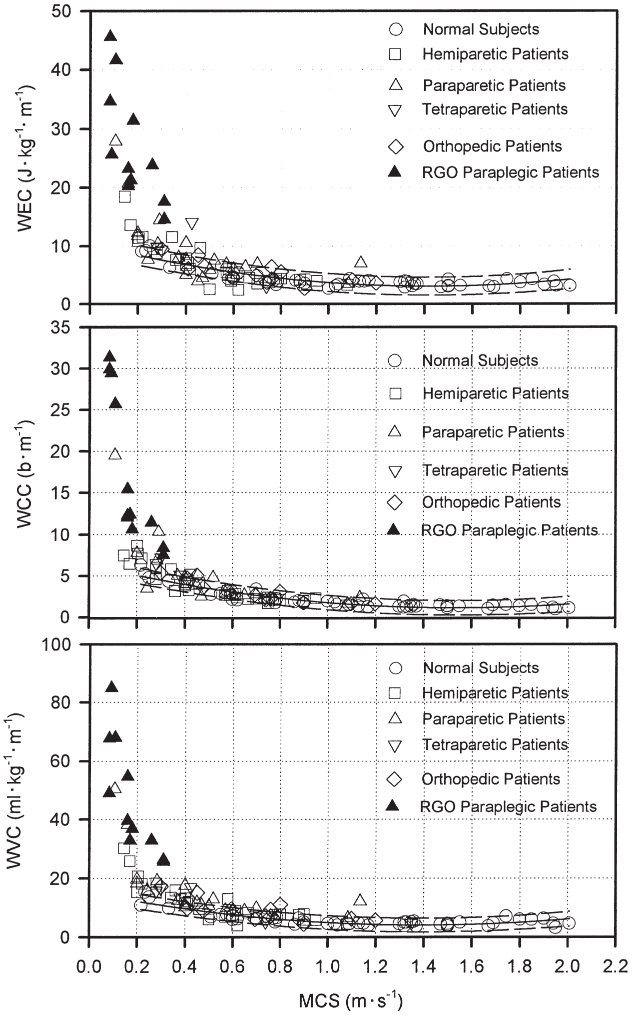

Fig. 1. Walking energy cost (WEC) vs. walking speed (top panel), walking cardiac cost (WCC) vs. walking speed (middle panel) and walking ventilatory cost (WWC) vs. walking speed (bottom panel): the data of all the subjects are shown. Each graph shows also the second order polynomial best fitting curve (solid line) and its prediction interval (dashed line).

Table 3
Correlation coefficients of the multiple linear regression analysis between MCS, WEC, WCC, WVC and CIS

	CIS	WEC	WCC	WVC	MCS
CIS	1				
WEC	−0.74	1			
WCC	−0.70	0.93	1		
WVC	−0.73	0.92	0.95	1	
MCS	0.80	−0.64	−0.61	−0.65	1

Table 4
Correlation coefficients of the multiple linear regression analysis between MCS, WEC, WCC, WVC and CIS excluding normal subjects and RGO patients

	CIS	WEC	WCC	WVC	MCS
CIS	1				
WEC	−0.42	1			
WCC	−0.47	0.93	1		
WVC	−0.41	0.96	0.92	1	
MCS	0.57	−0.70	−0.69	−0.71	1

widely scattered around the mean, both in patients of groups A, B, C and D and in normal subjects.

In light of the previous statistical test, a further ANOVA post hoc test was performed grouping the patients into three categories: RGO patients, dependent walkers (DW) and independent walkers (IW). A fourth category included normal subjects (N). In Table 1 the number of IW and DW is given for each group of subjects. Table 6 shows the mean values and the standard deviations of MCS, WEC, WCC, WVC and CIS for each of the four categories of subjects. Table 7 shows the level of significance when the statistical difference between groups was present. In both the RGO patients and the DW category, all of the parameters considered were found to be significantly different from those of all other categories of subjects. The patients who were able

Table 5
One-way ANOVA with the student-Neuman–Keuls post hoc test: comparison of the differences in CIS, physiological costs (WEC, WVC, WCC) and MCS among the various groups. Hemiparetic (A), paraparetic (B), tetraparetic (C), orthopedic (D), RGO (E) and normal subjects (F). S indicates a significance correlation with a P value lower than 0.05. N.S. indicates a non-significant correlation

	A	B	C	D	E	F
WEC						
A	X					
B	N.S.	X				
C	N.S.	N.S.	X			
D	N.S.	N.S.	N.S.	X		
E	S	S	S	S	X	
F	N.S.	S	N.S.	N.S.	S	X
WCC						
A	X					
B	N.S.	X				
C	N.S.	N.S.	X			
D	N.S.	N.S.	N.S.	X		
E	S	S	S	S	X	
F	N.S.	S	N.S.	N.S.	S	X
WVC						
A	X					
B	N.S.	X				
C	N.S.	N.S.	X			
D	N.S.	N.S.	N.S.	X		
E	S	S	S	S	X	
F	N.S.	S	N.S.	N.S.	S	X
CIS						
A	X					
B	S	X				
C	N.S.	N.S.	X			
D	N.S.	S	N.S.	X		
E	S	S	S	S	X	
F	S	S	S	S	S	X

to ambulate without assistance devices (IW), despite having a CIS and MCS significantly lower than those of normal subjects, did not have physiological costs statistically different from those of normal subjects. It is important to stress that the patients who had a physiological cost beyond the prediction interval of the control group (see Fig. 1) were the subjects included in the RGO and DW categories, that is, the most impaired patients.

Table 7
Levels of significance obtained with ANOVA and post hoc tests performed grouping the patients as dependent walkers (DW), independent walkers (IW), RGO patients (RGO) and normal subjects (N)

	DW	IW	RGO	N
WEC				
DW	X			
IW	$P = 0.004$	X		
RGO	$P = 0.0001$	$P = 0.0001$	X	
N	$P = 0.003$	N.S.	$P = 0.0001$	X
WCC				
DW	X			
IW	$P = 0.003$	X		
RGO	$P = 0.0001$	$P = 0.0001$	X	
N	$P = 0.014$	N.S.	$P = 0.0001$	X
WVC				
DW	X			
IW	$P = 0.06$	X		
RGO	$P = 0.001$	$P = 0.0001$	X	
N	$P = 0.01$	N.S.	$P = 0.0001$	X
CIS				
DW	X			
IW	$P = 0.0005$	X		
RGO	$P = 0.0001$	$P = 0.0001$	X	
N	$P = 0.0001$	$P = 0.0001$	$P = 0.0001$	X
MCS				
DW	X			
IW	$P = 0.0001$	X		
RGO	$P = 0.0005$	$P = 0.0001$	X	
N	$P = 0.0001$	$P = 0.0001$	$P = 0.0001$	X

4. Discussion

Although a simple method to assess locomotor impairment is desirable in the clinical setting, the results of this study show that more than one measure may be useful for a more comprehensive evaluation of a patient. If the main goal is to have a single measure of locomotor impairment, the speed spontaneously adopted by the patient should be used as a parameter of judgment.

In each group of patients, the most comfortable speed (MCS) was significantly lower than that of normal subjects. The MCS of normal subjects was about seven times faster than that of RGO paraplegic patients and twice as fast as that of the other patients (see Table 2).

Table 6
Walking energy cost (WEC), walking cardiac cost (WCC) and walking ventilatory cost (WVC) at the most comfortable speed (MCS), in different categories of subjects grouped as dependent walkers (DW), independent walkers (IW), RGO patients (RGO) and normal subjects (N)

Subject group	No. of subjects	MCS (m s^{-1})	WEC (J kg^{-1} m^{-1})	WCC (beats m^{-1})	WVC (ml kg^{-1} m^{-1})	CIS
DW	24	0.45 ± 0.22	8.57 ± 4.78	4.9 ± 3.2	14.4 ± 8.24	1.24 ± 0.23
IW	44	0.7 ± 0.3	4.9 ± 2.62	2.58 ± 1.11	8.1 ± 3.9	1.4 ± 0.2
RGO	11	0.17 ± 0.08	27.2 ± 9.9	17.67 ± 9.3	47 ± 19.5	0.4
N *normal speed*	18	1.28 ± 0.17	3.53 ± 0.466	1.47 ± 0.26	4.55 ± 0.56	

Conversely, only in the most impaired patients (RGO patients and dependent walker patients) were the physiological costs significantly greater than for normal subjects.

The cost of walking in normal subjects is speed-dependent, and is exponentially greater as the walking speed is reduced [12]. To build the second-order polynomial curve that describes the relationship between physiological costs and speed, normal subjects were requested to walk not only at their MCS but also at faster and slower speeds. The latter speeds were actually the speeds of almost all our patients. As mentioned in the Introduction and as discussed later, some authors have assumed that the difference in speed alone explains the different cost when normal subjects are compared with patients. In fact, the patients were only able to walk at a slow speed; that is, it was very hard and tiring for them to change their natural walking speed [17]. This means that if a patient tried to increase his/her speed, his/her cost would increase; however, if a patient had a faster MCS, his/her cost would decrease, because he/she would "move" into a portion of the WEC versus speed curve with higher efficiency [9]. Furthermore, all our patients manifested a significant degree of locomotor impairment in addition to slow speed. They had asymmetry of right or left stride and defective kinematics of one or both legs. However, 47 out of 82 patients had their energy cost within the prediction interval of normal subjects. It is controversial whether the walking speed spontaneously adopted by a patient and the walking energy cost can be used interchangeably to assess the locomotor impairment. Some studies have shown that metabolic demands for orthopedic patients [4,5,10,8] and for neurological patients [1,7] are greater than for normal subjects walking at the same speed. Other authors maintain that when normal subjects were requested to walk at the same slow speed as disabled subjects, differences in locomotor costs were reduced or disappeared [3,6,10]. In other words, these authors hypothesize that the measurement of speed alone could serve as an index of locomotor impairment, because it already provides information about the physiological costs. Our results could explain both of these previously mentioned positions. In fact we have some patients (44% of the total) in whom the physiological costs are above the upper limit of the prediction interval of normal subjects. In these patients the measurement of the MCS alone could be misleading. Further analyses of our patients demonstrated that these patients are actually the most impaired patients, for whom we have to take into account extra work due to the fact that they have to move their walking device. Therefore, we can suppose that the authors who sustained the interchangeability of physiological costs and MCS probably evaluated patients who were not very severely impaired. These conclusions are in accordance with those of Zamparo et al. [9], who sustain that the differences in WEC between normal subjects and patients occurred only when the latter walked at a very slow speed. In fact, in some of our hemiparetic patients (group A) with a slow MCS the energy cost was similar to that of normal subjects at a slow walking speed. Pain, balance, fear of falling, and stiffness of joints or muscles (spasticity), rather than limited energy availability, may be contributing to a reduced speed of ambulation. Although the literature [1,7] indicates that some of these factors contribute to both increased energy requirements and reduced speed, more precise studies are needed.

It should be considered that the patients, if they had trained, may have developed a more efficient locomotor pattern for their MCS [19] compared with normal subjects who are not used to such slow speeds. For these reasons, normal subjects may not serve as the appropriate controls in studies of patients with mild locomotor impairments. Using patients as their own controls in longitudinal studies is more desirable when assessing the effects of interventions. Because of these factors, the WEC alone cannot be assumed to be an absolute sign of locomotor integrity. In other words, we cannot assume that a patient with a WEC in the normal range is not impaired, particularly if the physical impairment is not severe. WEC alone can be reliable in assessing locomotor impairment in very severely impaired individuals as shown by our results. In fact, the patients requiring canes, crutches and walkers had a WEC twice as high as normal subjects. The patients with complete paralysis of that of the lower extremities requiring orthoses (RGO) had an energy demand which was almost five times higher than that of normal subjects. It should be stressed that the RGO patients could not stand up and walk at all without the orthosis, and of course this kind of walking not only has a poor efficiency, but requires high mechanical work [20]. In both the DW and RGO patients the increased energy cost is obviously due also to the mechanical work that they have to perform in order to move their device. That is, their inability to ambulate without this device decreases still further their walking efficiency, already low because of their low speed and impairment.

The concepts mentioned above related to WEC also apply when the walking cost is measured as cardiac (WCC) or ventilatory (WVC) extra load. Particularly, the heart rate correlates very well with WEC and appears to be a particularly reliable parameter in younger subjects [2]. However, it has both advantages and disadvantages. Measuring heart rate is easier and less expensive than measuring oxygen intake. However, anxiety and, in older subjects, irregular rhythm or drugs such as beta-blocking agents may reduce its reliability. In addition, the response of the heart to exercise is dependent on the previous training of the subject and a well conditioned person can exhibit a lower heart rate at parity of work load than a less fit subject. Indeed, WEC and WCC reflect different adaptations to physical exercise. Both of them have been demonstrated to be very useful indices of the improvement in walking ability when longitudinal studies are performed to test the effect of a rehabilitation treatment [19]. WEC depends mainly on the mechanical work performed. Therefore, WEC is not expected to decrease, after an initial improvement in the efficiency, if the mechanical work performed stays stable. On the other hand, especially after a long rehabilitation period (such as six months), the WCC can decrease as a result of a long-term cardiovascular adaptation.

Aside from the limitations of the WEC or the WCC in serving as a single measure of walking impairment, the most comfortable speed is definitely the easiest parameter to measure and appears to be the most reliable when judging the condition of a patient for all types of locomotor impairment. In this case the reliability is based on the significant difference between the MCS of each group of patients and the MCS of normal subjects (ANOVA). Because only a few patients (less than 5%) were able to walk at a speed comparable with that of normal subjects, it is almost impossible to run the risk of a false negative in the measurement. There is a significant negative linear correlation between preferred speed and each physiological cost (energy, cardiac and ventilatory cost), which guarantees at least a partial inter-relationship of these measures. The MCS, having the highest correlation with the CIS (that is, the locomotory impairment based on two clinical scales), is also the parameter that in turn reflects the clinical severity of the pathology. According to previous work [17] we attributed to all subjects a score related to their walking ability (CIS) based on two clinical scales, one for the impairment [15] and a more specific one for the disability [4]. Our CIS could be criticized. A functional ambulation scale reliable for each kind of patient needs to be developed, similar to the one used in animal trials [21]. This could be the reason why, when RGO patients and normal subjects (i.e., the subjects with the highest and lowest CIS) were excluded from the correlation analysis, the correlation coefficients between the CIS and the other parameters decreased. Conversely, the physiological costs and the MCS increased relatively, demonstrating that the relationship between MCS and physiological costs is stronger than the relationship between the CIS and the other parameters. One major criticism can be made of this parameter: it is difficult to be sure that the subject is really walking at the MCS and not either slower or faster. Only good preparation of the subject and the right duration of the test can avoid the risk of this kind of mistake. The reserve that we have about this parameter is that it is possible to underrate the severity of the impairment. In fact, a subject with a low speed is definitely impaired but a patient who, at the same low speed also has a physiological cost above the prediction interval for normal subjects, is much more impaired. For the above-mentioned reasons, we agree with the authors who sustain the importance of the measurement of energy cost for the clinical assessment of walking-impaired patients [1,4,5,9,22].

5. Conclusions

1. The walking speed spontaneously adopted by a patient is the most reliable index of motor impairment when compared with the clinical scores (CIS). Therefore it should be the best single measure of locomotor impairment if, for practical reasons, there is no time for a complete evaluation.
2. On the other hand, all the indices we studied are highly correlated with the CIS.
3. In the majority of patients all the physiological costs are dependent on their slow walking speed; i.e., some factors other than low muscle efficiency may be considered to limit the walking speed.
4. The physiological costs were found to be strongly correlated with one another and are useful indices of the most severe impairment. In fact, all the RGO patients and about 35% of the remaining patients (practically all the dependent walkers) showed physiological costs above the normal prediction intervals.
5. More precise measurements to globally assess locomotor impairment, such as the measurement of physiological costs, are necessary in clinical trials and in a longitudinal study of a patient.

Acknowledgements

This work was partially supported by a grant from the “Ministero Italiano della Sanità” (CAMARC–II, CEC Programme, Project A-2002, September 1994). We thank Dr Richard Baratta for his useful suggestions regarding the statistical treatment of the data.

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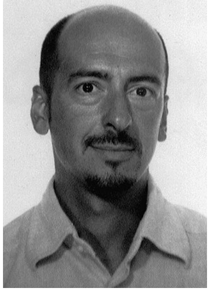

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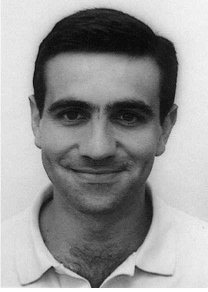

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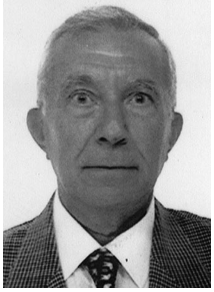

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