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Energy Cost of Walking with Hip Joint Impairment

Maristella Gussoni, Vittoria Margonato, Roberto Ventura and Arsenio Veicsteinas

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The energy cost of walking was measured in 12 patients (age 39–73 years) with hip joint impairment and 10 healthy controls during unassisted walking (2–6 km·h^{-1}) on a level treadmill surface and on a 5% incline. The energy cost of locomotion in most patients increased up to 50% and 70% during level-surface and uphill walking, respectively. This difference between patients and controls was probably due to the increased external mechanical work. The energy cost of walking, although related to pain experienced during walking but not to hip joint range of motion or to joint status evaluated radiographically, provides an additional variable when defining the conditions of disability and functional impairment in individuals with this pathological condition. [Gussoni M, Margonato V, Ventura R, et al: Energy cost of walking with hip joint impairment. Phys Ther 70:295–301, 1990]

Maristella Gussoni
Vittoria Margonato
Roberto Ventura
Arsenio Veicsteinas

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The energy cost of uphill, downhill, and level-surface treadmill walking in healthy subjects has been carefully investigated during the past 50 years. Researchers agree that the highest efficiency (least amount of energy required to cover a unit of distance) is reached during level-surface walking at 4 to 5 kilometers per hour (km·h^{-1}).[1–3] In this condition, the oxygen consumption ($\dot{V}O_2$) in healthy subjects has been found to average about 100 mL per kilogram of body weight per minute.[1–4] At higher and lower speeds, the energy cost per unit of distance walked increases hyperbolically. Disabled patients or those with lower limb amputation, using different kinds of canes or crutches, have been shown to consume much more oxygen than healthy individuals.[5,6] An increase of up to 20% in the energy cost of locomotion was also found in patients affected by minor foot lesions with an apparently normal gait.[7]

Most patients with functional hip impairment are in their fifth decade of life or older and consequently have age-related decreases in maximal heart rate (HR_{max}) and maximal oxygen consumption ($\dot{V}O_{2\,max}$). Chronic heart and lung disease, often seen in this age group, may be responsible for a further decrease in both of these variables.[8] Therefore, in the elderly individual affected by hip joint impairment, the energy cost of walking may approach the individual's $\dot{V}O_{2\,max}$.

One consequence of high relative exercise intensity is fatigue. Surgical intervention for total hip replacement, therefore, may be worthy of consideration in the elderly individual affected by hip joint impairment. Other than Pugh's single observation[5] and McBeath et al's self-selected velocity data,[9] we were unable to find studies in the literature on the energy cost of walking in patients with hip joint alterations. The purposes of this study, therefore, were 1) to determine the energy cost of level-surface and uphill walking at different speeds up to the maximum speed tolerated by patients with hip joint impairment, 2) to compare the results obtained with those of a control group, and 3) to relate the energy cost of locomotion to each

M Gussoni, ScD, is Assistant Professor of Physiology, Dipartimento di Scienze e Tecnologie Biomediche, Università di Milano, Via Olgettina 48, Milan, Italy 20132. Address all correspondence to Dr Gussoni.

V Margonato, ScD, is Assistant Professor of Physiology, Dipartimento di Scienze e Tecnologie Biomediche, Università di Milano.

R Ventura, MD, is Associate Professor of Clinical Orthopedics, Università di Milano, Via Bignami 1, Milan, Italy 20126.

A Veicsteinas, MD, is Professor of Physiology, Dipartimento di Scienze Biomediche e Biotecnologie, Università di Brescia, Via Valsabbina 19, Brescia, Italy 25125.

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Table. *Patient Data Obtained by Medical History and Radiographic Evaluation*

Patient Number	Age (yr)	Sex	Etiology	Hip Joint Range of Motion (°)	Degree of Hip Joint Impairment[a]	Maximum Walking Speed (km·h^{-1})	Pain During Walking[b]
1	61	M	posttraumatic	0–90	++	4.0	+++
2	55	M	dysplastic	0–90	+++	4.0	+
3	42	F	dysplastic	0–90	++	5.1	++++
4	48	F	idiopathic	0–80	++	4.7	++++
5	58	F	idiopathic	0–75	+++	4.3	++
			bilateral	0–80			
6	62	F	idiopathic	0–70	+++	4.0	+
7	49	M	idiopathic	0–60	+++	3.2	++++
			bilateral	0–90			
8	39	F	posttraumatic	0–70	+++	5.2	+
9	73	M	idiopathic	0–40	++++	2.0	++
10	65	F	idiopathic	0–45	++	5.5	++
11	58	M	idiopathic	0–30	++++	5.1	++
12	62	M	idiopathic	0–30	++++	3.8	++

[a] ++ = reduction and thickening of cotyloid rim; +++ = acetabular rim still visible, but notably reduced by osteophytes; ++++ = almost complete disappearance of acetabular rim with large osteophytes along margin.

[b] + = slight pain only at high speed; ++ = slight pain unchanged at high speed; +++ = severe pain at highest speed; ++++ = severe pain at low speed.

patient's functional impairment and subjective symptoms.

Method

Subjects

The study was carried out on 12 patients with hip joint impairment and 10 control subjects. From a large group of patients scheduled for total prosthetic hip replacement, only 12 individuals (6 male, 6 female), aged 39 to 73 years, could walk unassisted and were accepted for participation in the study (Table). Controls were 10 healthy individuals of similar age (50–65 years) and body size. All subjects signed an informed consent form, which had been previously reviewed and approved by the scientific review board of the hospital.

Clinical Investigation

The patients underwent a clinical inquiry and examination session prior to the start of the study (Table). Patients' histories revealed previous femur neck fracture (posttraumatic coxarthritis), congenital hip dislocation (dysplastic coxarthritis), or idiopathic coxarthrosis. Stature and body weight were recorded, and leg length from the anterior superior iliac spine to the internal malleolus was measured to reveal any asymmetry. Hip range of motion was close to normal values in extension. Hip flexion ROM was evaluated in the following way: With the patient in a supine position, the pelvis stabilized, and the legs extended (0°), the thigh was flexed on the pelvis and the maximum angle of flexion was recorded.

Radiographic evaluation included both anterior-posterior and axial projection radiograms. The severity of the impairment was based on the breadth of the acetabular rim, the presence of osteophytes, and the relative congruence of the femur head and acetabulum.

The patients' degree of hip joint impairment was graded in the following manner:

1. ++++ = almost complete disappearance of the acetabular rim with large osteophytes along the margin.
2. +++ = acetabular rim still visible, but notably reduced by osteophytes.
3. ++ = reduction and thickening of the cotyloid rim.
4. + = early signs of hip arthrosis with acetabular rim more or less intact.

Experimental Procedures

The study was performed in two stages. In the first stage, the patients, after consuming a light breakfast, came to the laboratory to familiarize themselves with treadmill walking. During this testing session, the maximum walking speed reached by each subject was determined during unassisted treadmill walking on a level surface and on a 5% incline.

A few days later, data collection began (stage 2). The procedure required the patient to walk unassisted on a level treadmill* and on a 5% incline at three or four different speeds until the maximum walking speed was reached. Between one trial and the next, there was a 30-minute rest period.

Oxygen consumption was determined by a standard open-circuit method. With a noseclip in place, the subject was connected by means of a mouthpiece and two-way respiratory valve to a Douglas bag where expired air was collected. The expired air was then analyzed using fast-response oxygen (O_2) and carbon dioxide (CO_2) gas analyzers,† calibrated with known gas concentrations.

Subsequent calculation of the volume of air expired per unit of time together with the analysis of O_2 and CO_2 gas fractions yielded the total oxygen consumption per minute (mL $O_2 \cdot min^{-1}$) in conventional temperature, pressure, and dry conditions. The $\dot{V}O_2$ at rest was determined from a three-minute expired air collection taken from each patient while standing on the immobile treadmill.

Treadmill speed was carefully checked both before and during each walking trial. The duration of each exercise was chosen on the basis of individual heart rate (precordial leads), which was continuously monitored during the trial by a cardiotachometer. Only when heart rate reached a plateau for a few minutes, indicating physiological steady state, was the expired air collected in two different Douglas bags for a total period of three minutes. The entire duration of each exercise trial was about 10 minutes. During walking, the stepping frequency was determined by counting the number of steps per unit of time (steps·min^{-1}).

During each trial, any pain reported by the patient was evaluated and graded by the investigator (RV) as follows:

1. ++++ = severe pain at low speed.
2. +++ = severe pain at the highest speed.
3. ++ = slight pain unchanged at high speed.
4. + = slight pain only at high speed.

Using the same procedure previously applied for patients, the $\dot{V}O_2$ and the stepping frequency were measured in the control group at 2, 3, 4, 5, and 6 km·h^{-1} during level-surface and 5% uphill walking, respectively.

Data Analysis

For each subject, the resting $\dot{V}O_2$ was subtracted from the $\dot{V}O_2$ measured at each walking speed to obtain the net oxygen consumption ($\dot{V}O_{2\ net}$). The $\dot{V}O_{2\ net}$ and stepping frequency for the control subjects at each walking speed and slope were averaged and two-standard deviation values were calculated. All two-standard deviation values were connected visually, yielding the two boldface curves shown in Figures 1 to 3. All values included between the two curves are within 95% of the total values observed in the control subjects.[10]

Assuming a normal population distribution, we can expect any value that falls outside these two curves, representing the 95% confidence limits, to be significantly different ($p < .05$) from control values.[10]

Results

The Table shows the maximum walking velocity, the hip joint ROM, the radiographic results, and the degree of pain experienced while walking for each participant in the patient group. Four patients (Patients 1–4) had a hip joint ROM between 80 and 90 degrees, four (Patients 5–8) had ROMs between 75 and 60 degrees, and the rest (Patients 9–12) had ROMs between 30 and 45 degrees. Note that a systematic trend between the maximum walking speed achieved and ROM cannot be established. The Pearson product-moment correlation coefficient (r) between these two variables was low (r = .47).

All patients could walk at a speed of 2 km·h^{-1} and 90% could walk at 3 km·h^{-1}, but only 50% were able to sustain speeds higher than 4 km·h^{-1} because of intolerable pain. The patients who reached a given speed on the level-surface treadmill were also able to maintain about the same speed on a 5% incline.

In Figure 1, the individual values of net oxygen consumption per unit of body weight per minute (mL $O_2 \cdot kg^{-1} \cdot min^{-1}$) are plotted against walking speed (km·h^{-1}) on a level surface and on a 5% incline. Each dot is the average of two subsequent determinations ($\dot{V}O_2$ difference less than 5%) obtained at the same speed. The parallel curves delimit the 95% confidence limits of the control values. As shown in Figure 1A, 52% of the trials performed on the level-surface treadmill (84% of the patients) demonstrated $\dot{V}O_{2\ net}$ values higher than the upper limit found in the control group, whereas in uphill treadmill walking (Fig. 1B), only 37% of the $\dot{V}O_{2\ net}$ values were above the normal range.

In Figure 2, the stepping frequency (steps·min^{-1}) maintained on the level and uphill treadmill surfaces is also plotted as a function of the walking velocity. As in Figure 1, the 95% confidence limits for the control values are delimited by the two parallel lines. In both experimental conditions (level surface and 5% incline), about 80% of the patients were capable of walking at a higher stepping frequency than the upper limit set by the control subjects, especially at lower speeds. As walking velocity increased, however,

*Jaeger GMBH, PO Box 5846, D-8700 Würzburg 1, Federal Republic of Germany.

†Beckman Instruments Inc, 3900 River Rd, Schiller Park, IL 60176.

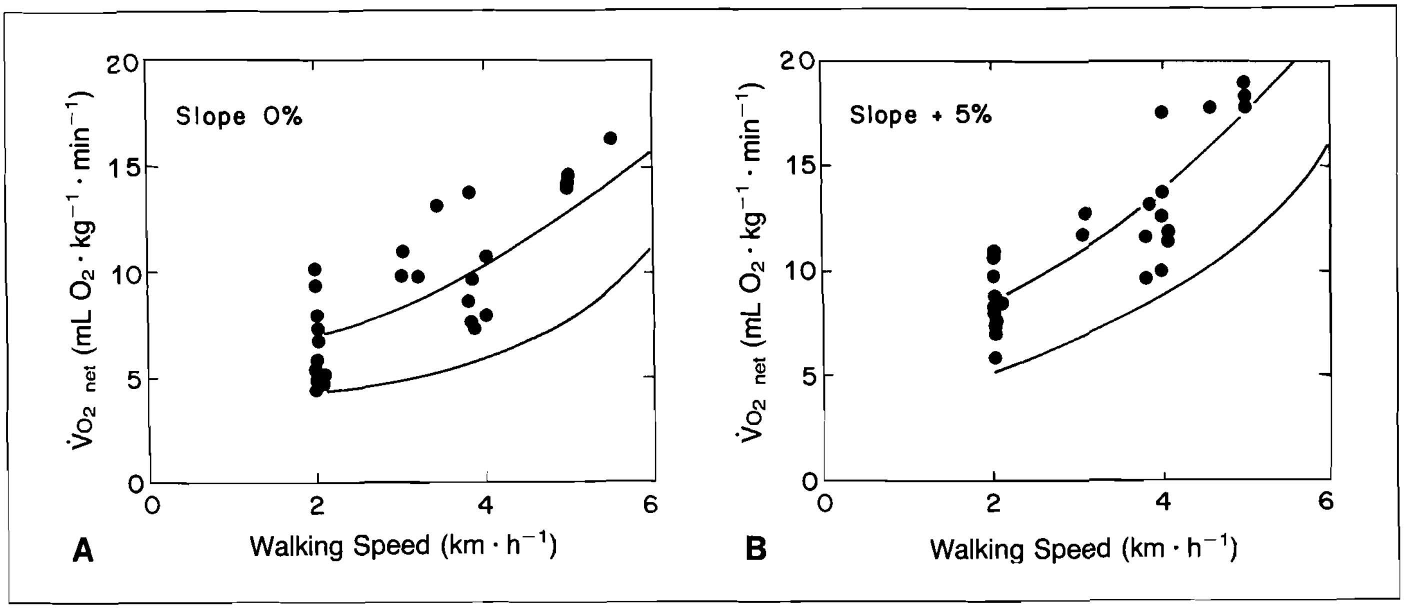

Fig. 1. *Net (actual minus resting) oxygen consumption ($\dot{V}O_{2\ net}$) (in milliliters of oxygen per kilogram of body weight per minute) as a function of walking speed (in kilometers per minute) during treadmill walking on a level surface (A) and on a 5% incline (B). The two parallel curves delimit the 95% confidence limits for healthy controls.*

the patients' stepping frequency demonstrated a tendency to return toward normal values.

In Figure 3, the net oxygen consumption per unit of body weight per minute divided by the stepping frequency ($\dot{V}O_2$·step^{-1}) is plotted as a function of walking speed during treadmill walking on a level surface (normal range recalculated from Figs. 1A and 2A). At a walking speed of 2 km·h^{-1}, patients demonstrated $\dot{V}O_2$·step^{-1} values that are significantly lower (up to 90%) than those of the controls. Most of these values increased toward normal values between the walking speeds of 3 and 4 km·h^{-1}. At the highest walking speed (6 km·h^{-1}), $\dot{V}O_2$·step^{-1} tended to be greater in the patients than in the controls. The uphill walking $\dot{V}O_2$·step^{-1} trend was similar to that observed for level-surface walking.

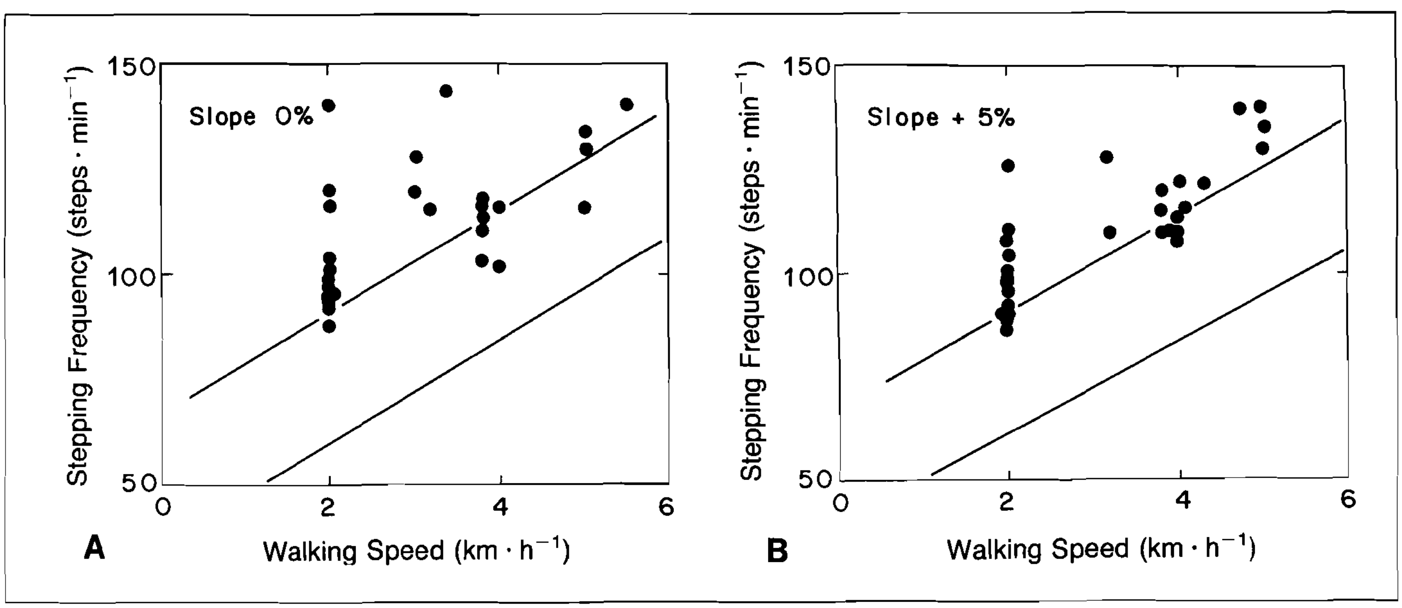

Fig. 2. *Stepping frequency (number of steps per minute) as a function of walking speed (in kilometers per minute) during treadmill walking on a level surface (A) and on a 5% incline (B). The two parallel lines delimit the 95% confidence limits for healthy controls.*

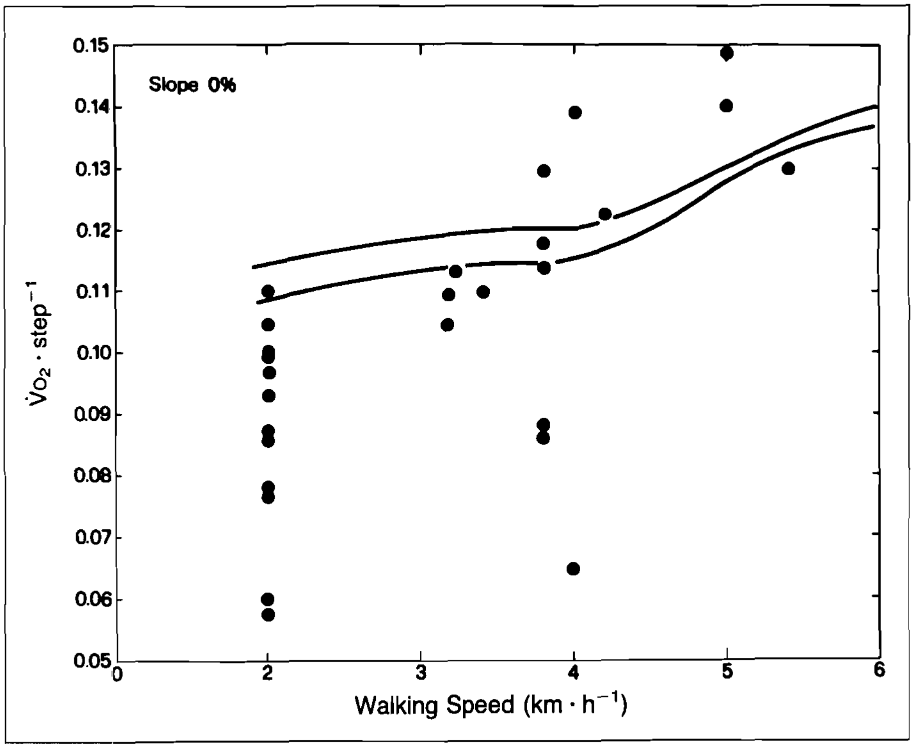

Fig. 3. *Net oxygen consumption per kilogram of body weight per minute divided by stepping frequency ($\dot{V}O_2 \cdot step^{-1}$) as a function of walking speed (in kilometers per hour) on a level surface. The parallel lines (calculated from Figs. 1A and 2A) delimit the 95% confidence limits for healthy controls.*

In Figure 4, the percentage variations in oxygen consumption ($\Delta\dot{V}O_2$%) and in stepping frequency (Δf%), with respect to average control values at any given speed, are plotted as a function of walking speed for the various degrees of referred pain. Patients with the maximum degree of pain (++++) had increased $\Delta\dot{V}O_2$% and Δf% values of up to 50% in comparison with controls. As the degree of the referred pain symptoms decreased, these values tended to decrease toward normal limits. However, the Δf% tended to remain beyond the upper normal range independently from the referred pain.

Discussion

Despite their hip joint impairment, all of the patients could walk comfortably on the treadmill once they were accustomed to the apparatus. The treadmill is particularly indicated in those studies of locomotion where quantifying the work load and maintaining constant velocity are important. When allowances are made for air resistances, which at low speeds are negligible, walking on the treadmill is practically equivalent to free surface walking.[11]

During this investigation, some of the patients were found to have asymmetrical lower extremities with leg-length differences of up to 15 mm. Nevertheless, in order not to alter their normal gait, the patients were asked to perform the treadmill trial wearing their usual shoes.

Several authors have found that $\dot{V}O_2$ during exercise in healthy subjects increases in a curvilinear fashion with increasing speed during both level-surface and uphill treadmill walking.[1,2,4,12] The variability found among young, healthy subjects averaged about ± 2 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$

While studying the energy cost of walking in healthy subjects of different age groups, Molina and Giorgi[13] observed, for the same walking velocities achieved by our patients, energy cost increases of 27% in 40-year-old subjects and 34% in 60-year-old subjects when compared with the energy cost calculated by Margaria[1] for 20-year-old subjects. Our control subjects were similar in age to the subjects in those studies; therefore, the normal values shown in Figures 1 to 5 take into account the variability between young and elderly subjects.

Pugh observed a $\dot{V}O_2$ of about 10 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$ at a speed of 2.5 $km \cdot h^{-1}$ and 16 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$ at a speed of about 5 $km \cdot h^{-1}$ in a patient with posttraumatic monoarticular arthritis.[5] These values are in good agreement with our data. Moreover, McBeath et al[9] showed that the $\dot{V}O_2$ at one speed (the most comfortable self-selected velocity, about 2.1 $km \cdot h^{-1}$) averaged 11.3 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$ (s = 2.6) in elderly patients ($\bar{X}$ age = 66 years, s = 7) before unilateral or bilateral total hip replacement. This average is comparable to that of our more severely impaired patients. The patients in our study suffered from hip diseases of different etiologies; however, the clinical pictures and symptoms were comparable.

Most patients in this study, regardless of the slope of the walking surface, experienced pain of increasing severity as walking speed increased, with associated increases in gait abnormalities. Pain prevented some patients from reaching walking speeds higher than 2 to 3 $km \cdot h^{-1}$

The energy cost of locomotion in our patients increased significantly ($p < .05$) in 52% of the trials performed on the level-surface treadmill and in 37% of those performed on the 5% incline. This finding was particularly true for uphill walking at high speeds where the total $\dot{V}O_2$ values approached 20 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$. Astrand and Rodahl have shown that healthy adult subjects beyond the fifth decade of age have a $\dot{V}O_{2\,max}$ of only 40% to 60% of that found at age 20 to 30 years. Assuming a $\dot{V}O_{2\,max}$ of 45 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$ for the 20- to 30-year-old age group, in a 50-year-

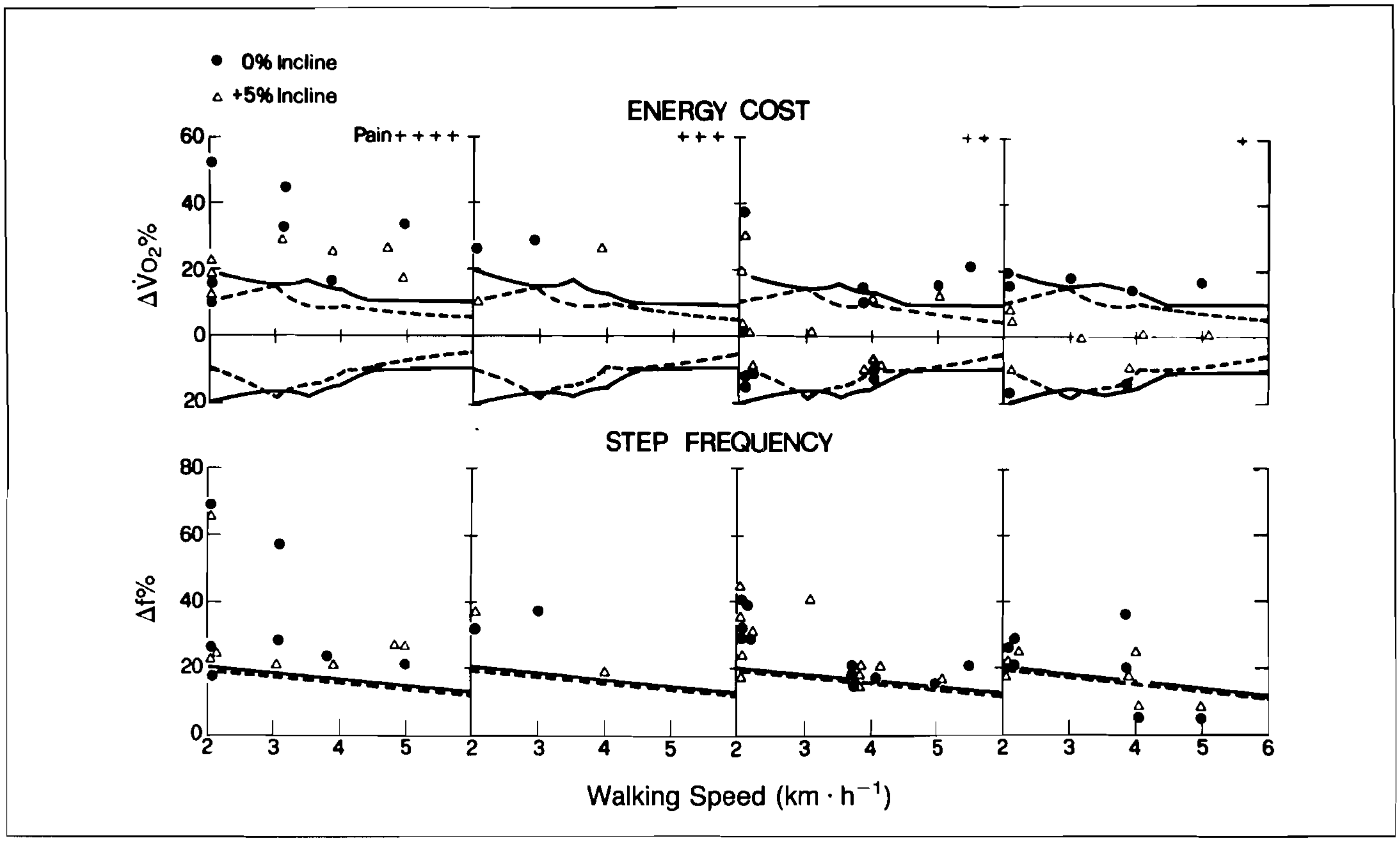

Fig. 4. *Percentage difference for oxygen consumption ($\Delta\dot{V}O_2$%) and for stepping frequency (Δf%) with respect to average values (0%) observed in controls as a function of walking speed on a level surface (●) and on a 5% incline (Δ). Continuous lines (level-surface walking) and dashed lines (uphill walking) delimit the 95% confidence limits for controls. (+ = slight pain only at high speed; ++ = slight pain unchanged at high speed; +++ = severe pain at highest speed; ++++ = severe pain at low speed.)*

old subject this value would drop to about 27 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$. Thus, the energy cost of walking at the highest speed found in some of our patients approaches the predicted $\dot{V}O_{2\ max}$ value for individuals of similar ages.

In addition to the increased $\dot{V}O_2$, stepping frequency also increased in about 80% of the trials performed on both level and uphill surfaces. The increase in the number of steps per minute was not proportional, however, to the increase in $\dot{V}O_2$ (Fig. 3). In 67% of the trials, the patients' $\dot{V}O_2 \cdot step^{-1}$ was much lower than in the controls, whereas in only 15% of the trials was it higher. In the trials with the higher values, the increase was observed only at walking speeds greater than 4 $km \cdot h^{-1}$. The observed increase in stepping frequency can be considered a compensatory mechanism, allowing locomotion despite severe impairment.

The causes of an increase in the energy cost of walking have been previously analyzed by Veicsteinas et al.[7] Therefore, only a few additional observations, restricted to studies involving individuals with hip disease, will be discussed in this article. Walking is characterized by a continual transformation of potential energy (a rise in the center of gravity) into kinetic energy. This transformation yields a substantial saving of energy with each step. When, for various reasons, this transformation is impaired, an increase in muscle activity is necessary; hence, a greater quantity of oxygen is consumed.

Abnormal gait patterns and pain may contribute to an increased energy cost of locomotion, but for different reasons. An abnormal gait pattern may produce asymmetry in stride (two successive steps), especially in cases of unilateral hip arthritis. The result is an unbalanced transformation from potential to kinetic energy and consequently an increase in the external mechanical work performed by the unaffected limb.[14,15] Pain, however, may increase muscle tone and compel the patient to shorten the length of the step. As a consequence, the patient compensates by increasing the stepping frequency at a given speed. These factors tend to increase the patient's $\dot{V}O_2$ because of an increase in the amount of activity per minute as compared with the healthy individual. When stepping frequency is augmented and step length is decreased, however, less deceleration is required as the foot strikes the ground; therefore, less external work is performed.[7,14,15] Evidently, the observed $\dot{V}O_2$ values are the result of a balance between those factors tending to increase the $\dot{V}O_2$ and the compensatory mechanisms tending to decrease the $\dot{V}O_2$.

An analysis of the data presented in the Table reveals that those patients who were found to have a greatly reduced hip joint ROM or whose radiographic picture demonstrated serious alterations were equally able to sustain relatively fast walking velocities. The factor limiting the performance of our patients in the 10 minutes of exercise seems to be pain symptoms, which were always accompanied by an evident abnormal gait.

Figure 4 demonstrates that, regardless of walking condition (level surface or incline), as the hip pain decreased, the $\dot{V}O_2$ values decreased to almost normal levels. It would seem, therefore, that the combination of pain and abnormal gait may play a major role in the elevation of $\dot{V}O_2$ and thus of the energy cost of walking, which in the elderly individual may even approach $\dot{V}O_{2\,max}$ values.

Conclusion

Patients with hip disease are impaired during walking, not only because of the accompanying abnormal gait and pain, but also because the energy required to walk during daily activity is increased. Such an increase has been found to be especially related to pain. In the more impaired and elderly patient, the value might be so high as to approach the patient's $\dot{V}O_{2\,max}$. Thus, we believe that the physical therapist should consider the energy cost of locomotion at different walking speeds up to the maximum walking speed achievable to more objectively define the conditions of disability and functional impairment in patients affected by hip disease. In addition to other signs of patient improvement, the efficacy of the method of therapy adopted could be quantitatively evaluated by the tendency of the energy cost of locomotion to reach normal values.

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