Realtime Visual Feedback Diminishes Energy Consumption of Amputee Subjects During Treadmill Locomotion

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ABSTRACT

Approximately 173,000 people in the United States are using lower limb prostheses. Although the design and use of prostheses have improved during the past 10 years, problems with energy expenditure still affect the gait of amputee patients. Realtime visual feedback (RTVF) has been shown to have an immediate effect on gait symmetry, although the effect on energy consumption was not measured. The aim of this study was to test the hypothesis that as amputees walk more symmetrically with the aid of RTVF, there will be a reduction in their oxygen consumption. Eleven amputee patients (mean age, 46 years; range, 36–58 years) participated. Three subjects were transfemoral amputee patients. Five tests were conducted for each subject: tests 1 and 5 were tests with no visual feedback, whereas tests 2, 3, and 4 involved walking while watching a computer screen that showed (1) left and right stance/swing ratios, (2) left versus right peak push-off forces and (3) a graph in which vertical and anteroposterior shear forces under each foot are plotted as vectors alongside each other, forming a so-called butterfly plot. As expected, there was a significant negative correlation between residual limb length and energy consumption during gait. In terms of possible future rehabilitation strategies, it was found that with each form of visual feedback there were significant improvements in both heart rate and oxygen consumption. In addition, the actual symmetry for the three forms of feedback improved across all subjects, indicating that the statistically significant improvements were not attributable to a placebo-type effect. The conclusion from these data is that RTVF not only results in an immediate improvement in symmetry, but there are also concomitant reductions in heart rate and oxygen consumption while walking at a steady pace on a treadmill. This implies that RTVF may serve as a useful aid in the successful rehabilitation of amputee patients. (*J Prosthet Orthot.* 2004;16:49 –54.)

In the United States alone, 115,000 to 135,000 lower limb amputations are performed annually. [1] The predominant factor leading to and accounting for approximately 70 percent to 90 percent of amputations is vascular disease, 10 percent to 20 percent are caused by a traumatic event, and tumors and birth defects each represent approximately 4 percent of the amputations performed each year. [2]

Energy consumption during ambulation is a major concern of both amputee patients and their physicians because it can have a significant effect on the rehabilitation process. Amputee patients may choose to forego completion of the proper rehabilitation program as well as lead sedentary lifestyles when the energy cost of ambulation is too high. [3] This is particularly relevant for transfemoral patients. In a study by Hagberg et al., [4] prosthetic use on a daily basis was documented in 96 percent of transtibial amputations, 76 percent of through-knee, and 50 percent of transfemoral amputations. Furthermore, 4 percent of the transtibial, 12 percent of the through-knee, and 39 percent of the transfemoral amputees reported absolutely no use of their prosthesis. The use of crutches to aid gait is not necessarily a solution because tachycardia can result. [5]

Symmetry indices have been applied as simple descriptors of pathology or used to monitor functional changes with treatment. It is usually assumed that gait symmetry and energy expenditure are related, but there have been only indirect tests of this hypothesis. Bach et al. [6] demonstrated a relationship between gait symmetry and oxygen consumption. In their study, gait symmetry was achieved by changing the mechanics of the prosthesis, rather than by training the amputees to walk symmetrically. The effect of realtime visual feedback (RTVF) on gait symmetry has been tested on transtibial amputees who walked on a treadmill. [7] Their device was designed to give feedback related to push-off forces and temporal events. The study showed that subjects were able to alter their gait pattern to become more symmetric (although the effect on energy consumption was not measured).

The aim of the current study was to test the hypothesis that as amputees walk more symmetrically with the aid of RTVF, there will be a reduction in their oxygen consumption. The clinical significance of the investigation was based on the belief that once a level of amputation has been selected by the surgeon, and once a prosthetic limb has been fitted, there may still be room for improving (i.e., reducing) the energy demands of amputee gait.

METHODS

Eleven amputee patients (mean age, 46 years; range, 36–58 years) agreed to participate and signed consent forms that were approved by the Institutional Review Board at the Cleveland Clinic Foundation. Three subjects were transfemoral amputee patients. Other subject-specific information is shown in Table 1 .

Gender	Level	Stature	Speed (km/hour)	Stump length	Classi-fication	Type of Prosthesis	Amputation	Age (years)

		(cm)		(cm)			Reason	
Male	BK	178	4.72	34.5	Long	Seattle Lite Foot (Seattle Systems, Poulsbo, WA)	Traumatic	36
Male	AK	182	4.2	29	N/A	Vertical Shock pylon Flex Foot (Ossur, Aliso Viejo, CA), Silicon suction socket, flexible inner socket, Blackmax knee frame with Mauch hydraulic unit (Ossur)	Traumatic	37
Male	BK	178	4	13.5	Normal	Silicon suction socket, Seattle Lite Foot (Seattle Systems)	Traumatic	54
Male	AK	183	3.9	44	N/A	SACH Foot (Otto Bock, Minneapolis, MN), suction suspension, flexible inner socket single axis knee with extension assist	Traumatic	52
Male	AK	181	4	29.5	N/A	Endolite Dynamic Foot (Endolite North America, Centerville, OH), suction suspension, flexible inner socket, Mauch hydraulic unit (Ossur), Endolite shock pylon, Tai Lin Graphlite knee frame (Daw, San Diego, CA)	Traumatic	53
Male	BK	172	3.9	23	Long	Silicon suction socket, College Park Foot (College Park Industries, Fraser, MI)	Traumatic	36
Male	BK	164	3.8	20	Long	Supracondylar suspension, Seattle Lite Foot (Seattle Systems)	Traumatic	47
Male	BK	184	3.9	27	Long	Silicon suction socket, Seattle Lite Foot (Seattle Systems)	Diabetic	43
Female	BK	163	3.4	12	Normal	Silicon suction socket, Endolite Multiflex Foot (Endolite North America, Centerville, OH)	Diabetic	45
Male	BK	175	4.1	14.5	Long	Endolite Dynamic Response Foot (Endolite North America), Pelite Insert (All Tech O & P Services, Fort Worth, TX), aluminum-titanium pylon	Traumatic	58
Male	BK	198	3.8	30	Long	Silicon suction socket, Allurion Flex Foot (Ossur)	Diabetic	50

After providing informed consent in accordance with Institutional Review Board procedures, subjects were asked to walk at a comfortable pace down the center of the laboratory. Their gait speed was recorded with a simple stopwatch as they traversed a known distance. This speed was used to set the subsequent speed of the treadmill.

Five tests, each lasting 4 minutes, were conducted for each subject: tests 1 and 5 were tests with no visual feedback; tests 2, 3, and 4 involved walking on an instrumented treadmill8 while watching a computer screen that gave various forms of visual information. Two of these (left and right stance/swing ratios and left versus right peak push-off forces; Figure 1a and Figure 1b) have been described previously. [7] The third (Figure 1C) involves a "butterfly plot" in which vertical and anteroposterior shear forces under each foot are plotted as vectors alongside each other. [9] Ground reaction force data were collected at 100 Hz.

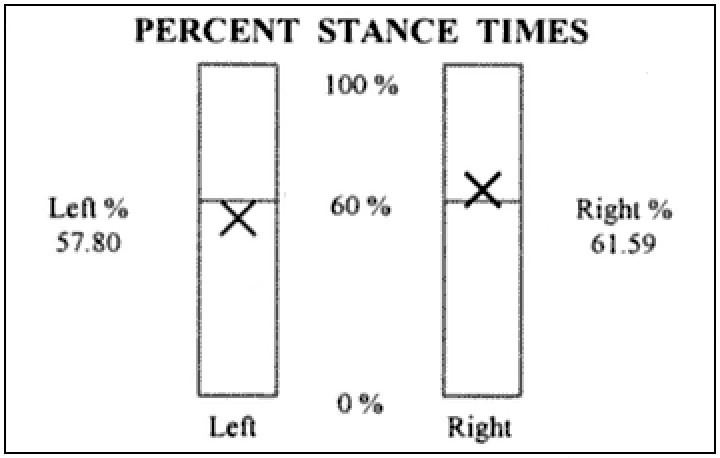

Figure 1-A. Display of stance/swing ratios. Typically a person would have a ratio of 0.6 (i.e., the stance phase accounts for 60 percent of the gait cycle). B: Display that represents the ratio of propulsive forces for each foot. If they are equal, the "x" is drawn in the center, and symmetry = 0.

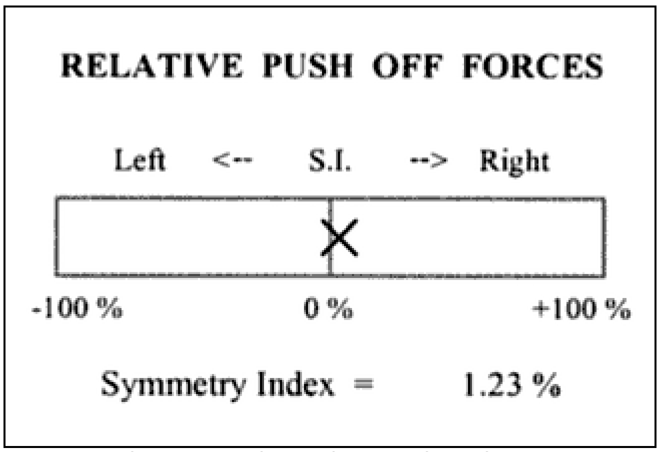

Figure 1-B. Display that represents the ratio of propulsive forces for each foot. If they are equal, the "x" is drawn in the center, and symmetry = 0.

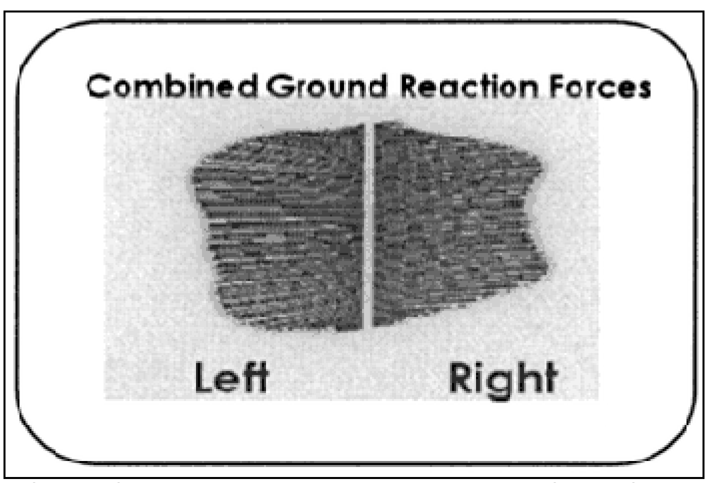

Figure 1-C. A "butterfly plot" for displaying realtime shear and vertical force information to each patient.

In all cases, patients were instructed to make the images as symmetric as possible. They had 4 minutes to "practice" gait modifications before data were collected. A cardiopulmonary stress test system (VmaxST, Sensor Medic Corp, Yorba Linda, CA) was used for measuring gas exchange parameters. An index of symmetry (SI) was calculated based on Dingwell et al.[7] :

Symmetry Index = $(X_{right} - X_{left})/(X_{right} - X_{left}) * 100\%$

where "X" represents a variable of interest, such as peak ground reaction force (for feedback involving either butterfly plots or push-off forces) or stance time (for feedback involving left and right stance/swing ratios). An index of zero reflects perfect symmetry. Once the indices of symmetry had been calculated for trials in which patients received feedback, these values were compared with the trials in which no feedback was given. These comparisons were based on the difference in absolute values, i.e., if a patient had a symmetry index of -6 percent without feedback, and +2 percent after feedback, their symmetry had improved by 4 percent. For subsequent statistical analyses, repeated measures analysis of variance (ANOVA; three levels of feedback versus no feedback) were used with alpha set at 0.05.

RESULTS

For each subject, the oxygen consumption (Figure 2) was similar to data reported more than 25 years ago, [10] despite that in the current study the technology for measuring oxygen involved a lightweight portable system, as opposed to a cart that had to be wheeled alongside the subject. In the current study there was no discernible effect caused by speed, although the range of self-selected speeds was relatively small Figure 2 and Figure 3). In terms of the oxygen consumed per meter traveled, for the traumatic amputee patients the data reflected what others have reported, i.e., less energy is required for amputations that are more distal (Figure 4). The effect of preserving each centimeter of a limb segment is reflected in both the oxygen consumption (Figure 5) and heart rate data (Figure 6).

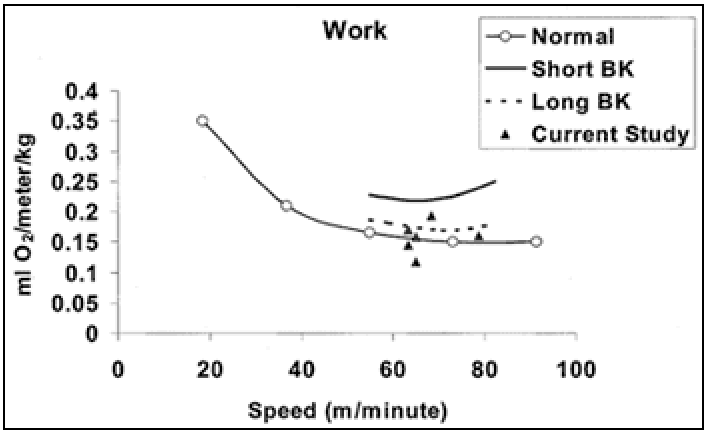

Figure 2. Oxygen consumption as a function of gait speed. The trend lines were obtained from Gonzalez et al. [10] Note that in the current study, the gait speeds were relatively consistent across subjects. Data from the current study represent transtibial subjects with residual limb lengths greater than 8 percent of total body height as classified by Gonzalez et al. [10] BK, below knee.

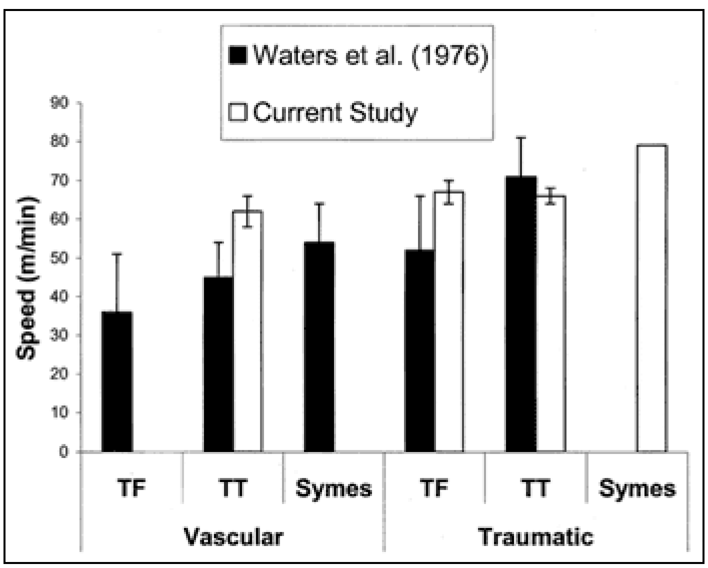

Figure 3. Comparison between the speeds of patients in the current study and those described by Waters et al. [5] TF, transfemoral; TT, transtibial.

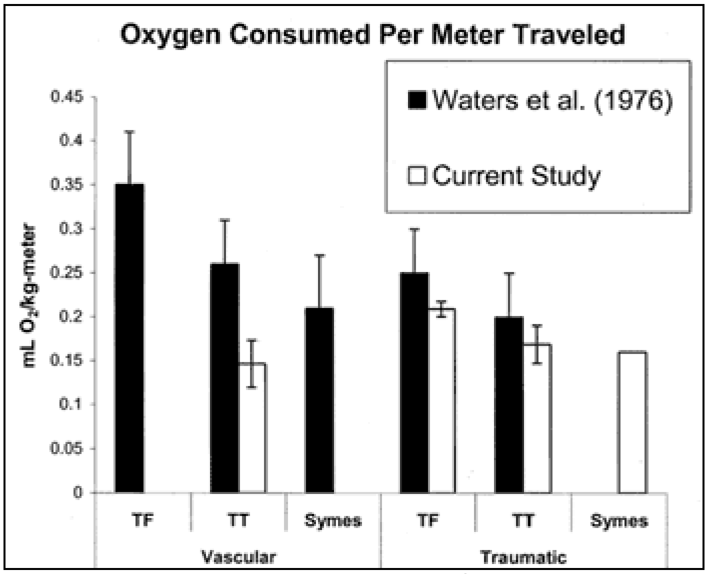

Figure 4. All of the vascular patients were transtibial patients. In the case of traumatic amputee subjects, as expected, the level of amputation had a significant effect on energy demands of gait. TF, transfemoral; TT, transtibial.

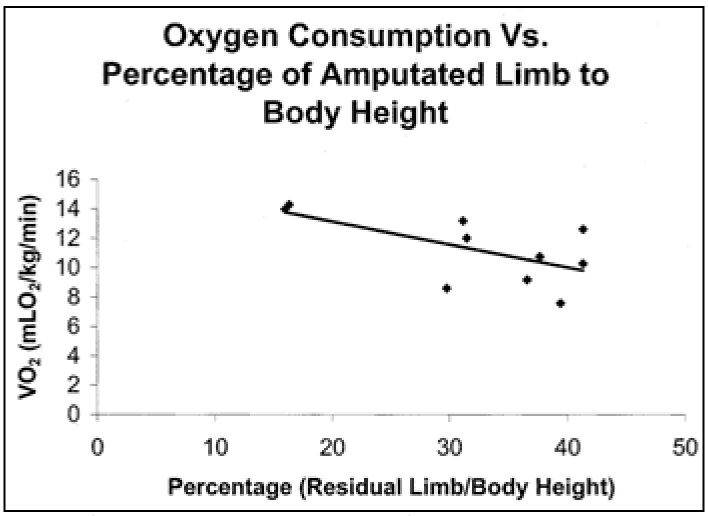

Figure 5. Oxygen consumption was significantly reduced as the level of amputation became more distal. Percentage is a ratio of the distance between greater trochanter and end of residual limb and total body height.

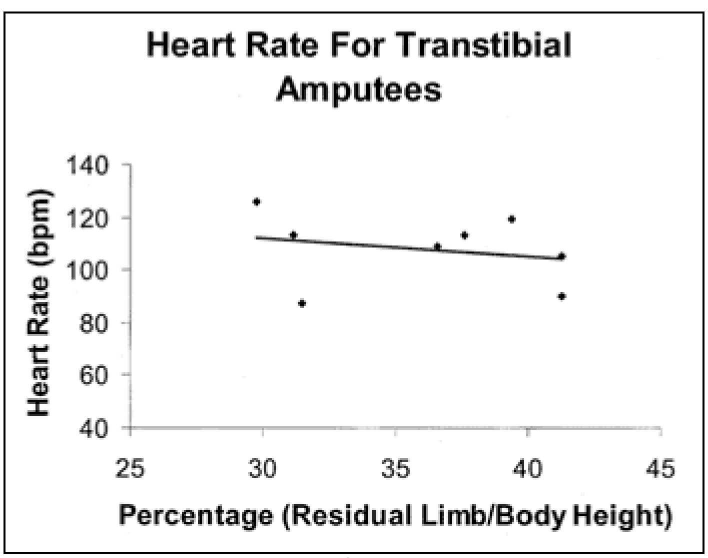

Figure 6. As the percentage of residual limb length (as measured from greater trochanter to distal end of residual tibia) with respect to total body height increased from 30 percent to 42 percent, the heart rate decreased by approximately 7 percent.

Of primary interest in the current study was the issue of whether patients could improve their energy expenditure by walking more symmetrically. When patients were given RTVF, there were significant improvements with each type of display and for each energy-related variable measured (Table 2). In addition, the actual symmetry for the three forms of feedback improved for all subjects, indicating that the statistically significant improvements were not attributable to a placebo-type effect (i.e., when patients knew they were supposed to walk more symmetrically) but were associated with quantitative improvements in gait symmetry.

Table 2. ***p*** **Values for the improvements in gait symmetry for three forms of RTVF**

	Butterfly plot	% Stance time	Push-off force feedback	% Difference*
VO_2	NS	NS	0.025	6%
Heart rate	0.05	0.006	0.04	3%
Tidal volume	0.005	0.002	0.004	22%
Symmetry improvements	6/9	7/11	8/11	

*The percentage difference corresponds to the improvement when realtime feedback is used.

DISCUSSION

EFFECT OF SEGMENT LENGTH

Based on clinical parameters, such as lowest palpable pulse, skin temperature, and bleeding during surgery, amputations are performed proximal to the level of irreparable damage or infected tissue. Surgeons keep as much length as possible while removing enough of the limb so that proper healing will occur at the distal end and future amputations are not necessary. Gonzalez et al. [10] reported that transtibial amputation with at least 9 cm of tibia preserved would result in performance far superior to that of knee disarticulation and transfemoral amputations.

Publications during the past 30 years have reported that as amputation level increases, energy cost of ambulation with a prosthetic device increases and self-selected walking speed decreases. The pathology underlying the need for an amputation is also a factor in rehabilitation. For instance, it has been shown that traumatic transtibial amputees are able to walk at faster speeds than are patients with transtibial amputations related to vascular disease. [5,11–13] Waters et al. [5] reported that the through-knee amputees had a self-selected walking speed falling between those of transtibial and transfemoral amputees. However, the O_2 consumption of a through-knee amputee was the highest of these three groups. Ankle disarticulation amputees were found to choose a walking speed higher than that of transtibial amputees, but the two groups were found to have the same metabolic cost for ambulation. Based on these findings, it is of interest to review the data shown in Figure 4 , where our findings suggest that transtibial vascular patients require less oxygen per meter traveled. Closer inspection of our data showed that the vascular transtibial patients had longer residual limbs (23 cm or 12.4 percent segment length) than did the traumatic amputations (17.8 cm or 10.4 percent segment length). Thus, in our cohort, it is likely the additional segment length compensated for the underlying reason for amputation.

Gonzalez et al. [10] reported the average self-selected walking speed of 64 m/min at an energy expenditure of 13.06 mL/ kg·minute for transtibial amputations caused by peripheral vascular disease. Pagliarulo et al. [12] reported that 15 vascular transtibial patients ambulated at 71 m/minute with an oxygen consumption of 15.5 mL/kg·minute. Gailey et al. [14] conducted study in which 39 nonvascular transtibial patients walked an average pace of 67.1 m/minute and had a metabolic energy expenditure of 12.9 mL/kg·minute. In the current study, vascular transtibial individuals had an average self-selected speed of 61.7 m/minute at an energy cost of 9 mL/kg·minute, and nonvascular transtibial amputee subjects had a speed of 65.8 m/minute at 11.2 mL/kg·minute.

EFFECT OF GAIT SPEED, AGE, AND SUBJECT MASS

Oxygen consumption (expressed as mL/kg/minute) during gait exhibits a linear relationship with the speed of walking according to the following equation1 [5] :

O_2 consumption = 0.1(walking speed) + 3.5, where speed is expressed in m/min.

In the current study, the coefficient was 0.082 (as opposed to 0.1 in the above equation), but this value was not statistically significant ($p > .05$). With regard to the effects of age, during a 22-year span, the regression coefficient was 0.055, although as with body mass, this was not statistically significant ($p > .05$).

Oxygen consumption is also a function of body mass, and investigators have shown that there is a significant positive correlation during walking between oxygen consumption and body weight. [16] Thus, oxygen consumption often is normalized to an individual's body mass when investigating weightbearing activities. Other factors, such as certain pathologies, also may influence oxygen consumption. Non– insulin-dependent diabetes mellitus and chronic lesions of the foot, two pathologies associated with limb amputation, have been shown to affect energy expenditure. Individuals with non– insulin-dependent diabetes mellitus have demonstrated, relative to healthy control subjects, a reduced rate of increase in oxygen consumption during increasing work loads, suggesting limitations in oxygen delivery. [17] With regard to lesions of the foot, rigidity of the talocalcaneal joint has been shown to result in a 5 percent to 20 percent increase in oxygen consumption, thus indicating increased energy expenditure. [18]

REAL-TIME VISUAL FEEDBACK

The problem of gait asymmetry has been examined by a number of researchers. Bach et al. [6] developed a computer simulation to minimize energy cost or maximize symmetry. He found that through optimizing the prosthetic limb's mass distribution there was a significant increase in gait symmetry and a decrease in energy expenditure. Furthermore, previous work by our group [7] showed that RTVF could lead to improvements in gait symmetry, even when the patients had been exposed to the computer displays for only 2 minutes.

In the current study, both symmetry and energy demands (as assessed by oxygen consumption and heart rate) were compared before and after patients received RTVF. The results showed that across all types of feedback, tidal volume had the most dramatic improvement (22 percent), compared with 6 percent and 3 percent improvements in VO_2 and heart rate, respectively. Subjectively, patients tended to prefer the "butterfly plot"; although in two of the subjects, there were some technical difficulties that prevented data for this form of feedback from being collected. Nevertheless, of the remaining nine subjects, six showed an improvement in symmetry when this form of feedback was used. For the percent stance time and push-off force displays, there were symmetry improvements in seven and eight subjects, respectively.

LIMITATIONS

There are certain limitations of the study that need to be recognized. First, this study required that patients wear a respiratory mask while walking on a treadmill. Although the patients seemed to cope well with both the oxygen measurement system and the treadmill, it is possible that the instrumentation constrained their walking patterns. Second, to have patients perform the full battery of tests (i.e., walking without feedback as well as three different feedback modes), only patients who could walk for the required length of time were accepted for this study. This limitation restricted the initial sample size, and it also means that the results should not be extrapolated to patients who have poorer locomotion capabilities. Third, patients were diverse in both their reasons for having an amputation and their type of prosthetic limb, leading to added variability in their gait mechanics and consequently in their energy expenditure. This limitation was partially addressed by having subjects serve as their own controls. Finally, these results, although encouraging, must be interpreted with caution because it is not yet clear that these changes in gait symmetry and oxygen consumption would result in long-term learning of a more symmetrical gait pattern. Because the primary goal of this project was to determine if amputee patients could respond positively to real-time visual feedback (i.e., use less energy during gait), and because this was shown to be the case, the questions of long-term gait-training effects are left to future research.

In summary, this study used three visual displays while patients walked on a treadmill, and all three were associated with significant improvements in energy consumption (Table 2). This suggests that even for patients who have had a suboptimal level of amputation, there may be forms of rehabilitation that can greatly increase the likelihood that they could walk more efficiently and have a higher level of daily mobility.

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