Effect of Amputation Level on Energy Expenditure During Overground Walking by Children with an Amputation

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Background: The oxygen cost of walking by adults with an amputation has been well described, but few studies have focused on this parameter in children who have had an amputation. Children with a transtibial amputation have been reported to maintain walking speed at a 15% higher oxygen cost than able-bodied children. The purpose of this study was to determine if the level of amputation in children has a differential impact on the self-selected speed of walking and the oxygen cost, and how the performance of these children compares with that of a group of able-bodied children.

Methods: Seventy-three children who had had an amputation participated in this study. Oxygen consumption was measured with a Cosmed K4b2 oxygen analysis telemetry unit (Rome, Italy) as the participants walked overground for ten minutes at a self-selected speed. One minute of steady-state data were reduced, averaged, and standardized to control values. Children with a unilateral amputation were grouped according to the level of the amputation; there were twenty-nine Syme, thirteen transtibial, fourteen knee disarticulation, five transfemoral, and five hip disarticulation amputations. Seven children had had a bilateral amputation, and they were considered as a separate group. Comparisons were made among the five amputation groups and between all children who had undergone amputation and control subjects. The variables that were analyzed were resting VO_2 rate (mL/kg/min), resting heart rate (beats per minute [bpm]), walking VO_2 rate (mL/kg/min), walking VO_2 cost (mL/kg/m), walking heart rate (bpm), and self-selected walking velocity (m/min).

Results: Unilateral transfemoral and hip disarticulation amputations resulted in significantly reduced walking speed (80% and 72% of normal, respectively) and increased VO_2 cost (151% and 161% of normal, respectively), while the heart rate was significantly increased in the hip disarticulation group (124% of normal). Compared with the controls, the children with a bilateral amputation walked significantly slower (87% of normal), with an elevated heart rate (119% of normal) but a similar energy cost. Children with a Syme amputation, transtibial amputation, or knee disarticulation walked with essentially the same speed and oxygen cost as did normal children in the same age group.

Conclusions: Children with an amputation through the knee or distal to the knee were able to maintain a normal walking speed without significantly increasing their energy cost. Only when the amputation is above the knee do children walk significantly slower and with an increased energy cost.

Level of Evidence: Therapeutic Level II. See Instructions to Authors for a complete description of levels of evidence.

Energy efficiency, evaluated by assessing oxygen consumption during gait, has been widely used as a functional outcome measure. Reported metabolic variables have included resting VO_2 rate (mL/kg/min), resting heart rate (beats per minute [bpm]), walking VO_2 rate (mL/kg/min), walking VO_2 cost (mL/kg/m), walking heart rate (bpm), and walking velocity (m/min). Published metabolic studies of adults with an amputation have demonstrated the effect of amputation level on VO_2 cost during gait[1], differences between patients with prostheses equipped with either an articulating or a locked knee joint[2], effects of residual limb lengths following below-the-knee amputation[3], and differences between patients who underwent the amputation because of vascular disease and those with a traumatic or acquired amputation[1]. Both overground[1-12] and treadmill[13-18] walking protocols have been used as tools to evaluate the walking ability of these individuals.

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Collectively, these studies have shown that adults who have had an amputation walk more slowly and at greater energy cost than adults who have not had an amputation. The authors of these studies concluded that the energy cost of walking increases as the amputation level ascends the lower limb[19].

Few studies have addressed these same issues in children who have undergone an amputation. Cadence parameters and heart rate during walking were studied in a group of children with various levels of amputation[20]. In that series, 58% of the children with an amputation had an increased heart rate compared with that of normal children, but most were able to maintain a normal walking velocity. Although many levels of amputation were included, the ability to appreciate differences between amputation levels was limited and the authors failed to include metabolic measures; thus, the issue of energy cost during walking was left in question.

Metabolic results in children who had undergone a transtibial amputation have been reported, with assessment of prosthetic foot type[21] and residual limb length[22] and with most investigators making comparisons with able-bodied children[21-23]. The size of the residual limb (short versus long) after the transtibial amputation was not found to have a significant effect on oxygen consumption[22]. VO_2 cost was shown to be higher in children using a SACH (solid ankle cushion heel) foot than in those utilizing a dynamic response foot[21]. Comparisons of children with a transtibial amputation and age-matched control subjects have shown conflicting metabolic data. In one study, VO_2 cost was reported to be increased by as much as 15% compared with control values[22], while other research showed no difference at all[21].

Since studies have shown differences in VO_2 cost between children and adults in the normal population[24], it is unclear if the energy-efficiency results reported in association with different levels of amputation in adults can be directly applied to the pediatric population. The purpose of the present study of children with a lower-extremity amputation was (1) to compare the energy efficiency between amputation levels and controls and (2) to compare published results in the adult amputation population with the results in a pediatric amputation population.

Materials and Methods

Participants

Between January 2002 and June 2009, the families of children who had had either a unilateral or a bilateral amputation, and wore prostheses, at our institution gave informed consent to participate in an institutional review board-approved study. Because all of the treatment had been completed prior to this time, this was an observational study with categorization of subjects according to the level of amputation, or as normal controls. Children with congenital or acquired limb deficiencies were included, with the exception of patients with the diagnosis of proximal femoral focal deficiency. Participants had to be free of neurological involvement and, if they had a unilateral amputation, free of involvement of the contralateral lower extremity. They had to have been able to walk independently (with the use of their current prosthesis) for more than four months and to be free of prosthetic complications, including an ill-fitting prosthesis, skin breakdown, or broken prosthetic components.

Prior to testing, an evaluation was performed to ensure proper prosthetic fit and function. Patients with malfunctioning prostheses were sent to a technician for repairs or were rescheduled to be tested on another day if the problem could not be immediately resolved. Unilateral amputations were categorized by the level of limb deficiency; the levels included Syme ankle disarticulation, transtibial, knee disarticulation, transfemoral, and hip disarticulation. All of the children with a bilateral amputation had had both amputations below the knee.

Testing Protocol

All participants were required to abstain from eating or drinking for at least two hours prior to testing. Metabolic testing was conducted with use of a Cosmed K4b2 oxygen analysis telemetry unit (Rome, Italy) in conjunction with a Polar S610i Heart Rate Monitor (Kempele, Finland). All patients were instructed to refrain from talking during the test, and hand signs were used for communication to minimize erroneous data points. Data were collected during a five-minute seated rest, during which the patient was instructed to maintain even breathing and to remain still. A ten-minute walk at a self-selected velocity was then performed around a 40-m loop. Lap times were collected with use of a stopwatch and were monitored to ensure a steady pace. At the conclusion of the walk at the self-selected velocity, the participants were seated for an additional three minutes to recover.

One minute of steady-state data, both from the rest period and from the ten-minute walking bout, was selected by a single investigator (K.A.J.).

Metabolic testing was conducted on normal control subjects in a separate prospective institutional review board-approved study involving children between six and nineteen years of age who had no orthopaedic or neurological involvement. Because of expected changes in metabolism with the onset of puberty[19], the control subjects were split into two age groups: children six to twelve years old and teenagers thirteen to nineteen years old.

Metabolic measures included resting VO_2 rate (mL/kg/min), resting heart rate (bpm), walking VO_2 rate (mL/kg/min), walking VO_2 cost (mL/kg/m), walking heart rate (bpm), and self-selected walking velocity (m/min). Because of the effects of age on the results, the measures for the amputation group were converted into percentages of the mean of the measures in the age-appropriate control group. This transformation also made it easier to evaluate the mean value for an amputation group, with use of 100% as a uniform norm.

Statistical Methods

A one-way analysis of variance (ANOVA) was used to compare the means of the five amputation groups and the controls for the indicated measures. If the ANOVA p value was <0.05, the Tukey multiple comparison method was used to determine which group means significantly differed from the others, while con-

TABLE I Demographics for Children with an Amputation and the Control Group

	No.	Age* *(yr)*	Weight* *(kg)*	Body-Mass Index* *(kg/m²)*	Sex *(no.)*		Diagnosis *(no.)*		
					Male	Female	Congenital	Disease	Trauma
Unilateral amputation									
Syme	29	11.1 ± 2.7	48.9 ± 21.2	20.4 ± 5.3	22	7	23	2	4
Transtibial	13	12.5 ± 3.8	50.0 ± 23.4	20.2 ± 4.7	8	5	7	1	5
Knee disarticulation	14	14.0 ± 3.5	55.1 ± 10.0	21.5 ± 2.6	6	8	5	6	3
Transfemoral	5	14.0 ± 2.1	55.5 ± 21.2	20.7 ± 5.8	2	3	0	4	1
Hip disarticulation	5	12.0 ± 5.0	42.6 ± 17.4	18.1 ± 2.4	4	1	1	4	0
Bilateral below-the-knee amputation	7	11.6 ± 5.1	59.4 ± 33.7	23.9 ± 8.8	2	5	6	1	0
Controls									
Children (6-12 yr)	24	10.0 ± 1.7	36.1 ± 7.5	16.9 ± 1.8	9	15			
Teenagers (13-18 yr)	21	15.7 ± 1.7	65.4 ± 19.1	22.4 ± 5.8	9	12			

*The values are given as the mean and standard deviation.

trolling the overall Type-I error level at 0.05. Comparisons between the control subjects and either the patients with a bilateral amputation or a subgroup of patients with a unilateral below-the-knee amputation were made with use of the two-sample t test, assuming unequal variances in the two groups. A more targeted comparison of amputation level with controls was performed by comparing the mean of each amputation level with a null hypothesis value of 100%. When groups were compared for differences in demographic variables, the one-way ANOVA was used.

Source of Funding

No external funding source played a role in this investigation.

Results

Subject Demographics

Seventy-three children with an amputation (forty-four males and twenty-nine females) between four and nineteen years of age underwent metabolic testing (Table I). Children with a unilateral amputation were divided into five groups according to the amputation level: there were twenty-nine Syme, thirteen transtibial, fourteen knee disarticulation, five transfemoral, and five hip disarticulation amputations. There was a separate group of seven children with a bilateral below-the-knee amputation. Children with an amputation due to congenital anomalies, limb loss due to trauma, or amputation due to disease were included in this analysis. Ten patients with proximal femoral focal deficiency were excluded. All patients were tested at least one year after gait training following their amputation and were considered acclimatized to their current prostheses.

There were forty-five control subjects (eighteen males and twenty-seven females) between six and eighteen years of age. Twenty-four were six to twelve years of age and twenty-one were thirteen to eighteen years of age. Metabolic data for each of these age groups can be found in Table II.

Unilateral Amputation Group

All study patients completed a five-minute seated rest. Analysis of variance (ANOVA) tests on anthropometric and resting variables failed to show significant differences between any of the amputation groups and the control subjects (body mass, p = 0.8606; body-mass index, p = 0.6164; resting VO_2 rate, p = 0.0979; resting heart rate, p = 0.6725). One-sample t tests comparing the amputation groups with the controls showed that the resting VO_2 rate was significantly above normal in the Syme amputation group (p = 0.0280) but not in any of the other groups. No amputation group differed significantly from normal with regard to the resting heart rate.

Figure 1 and Table III show the effect of the amputation level on the VO_2 rate, VO_2 cost, self-selected walking velocity, and heart rate during overground walking, with the mean results expressed as a percentage of normal. The trend of an

TABLE II Metabolic Data for the Control Group*

	Children (6-12 Yr) (N = 24)	Teenagers (13-18 Yr) (N = 21)
Resting		
VO_2 rate *(mL/kg/min)*	6.18 ± 1.23	5.15 ± 0.94
Heart rate *(bpm)*	84 ± 13	85 ± 12
Walking		
VO_2 rate *(mL/kg/min)*	18.04 ± 3.03	15.73 ± 2.71
VO_2 cost *(mL/kg/m)*	0.22 ± 0.03	0.20 ± 0.03
Velocity *(m/min)*	80.24 ± 7.56	77.20 ± 4.17
Heart rate *(bpm)*	115 ± 14	112 ± 13

*The values are given as the mean and standard deviation.

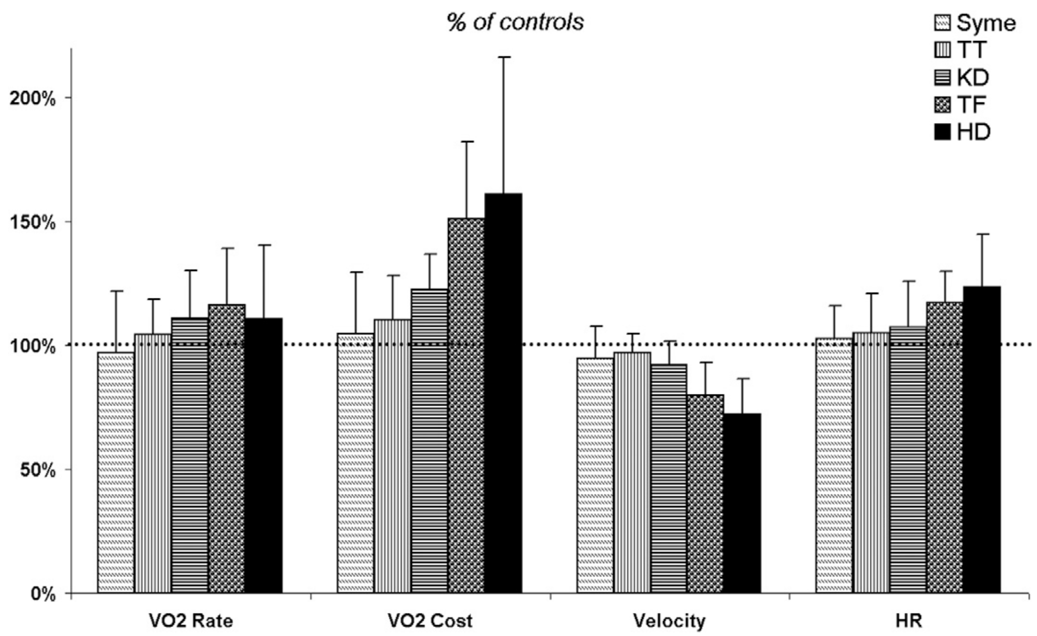

Fig. 1

Energy efficiency (and standard deviation), during walking, of children with a unilateral amputation presented as a percentage of normal for comparison across age groups. TT = transtibial, KD = knee disarticulation, TF = transfemoral, HD = hip disarticulation, and HR = heart rate.

increasing VO_2 rate with each higher level of amputation, as seen in Figure 1, failed to reach significance ($p = 0.1303$). The one-sample t test showed the walking VO_2 rate in the knee disarticulation group to be significantly above normal ($p = 0.0312$). To determine the VO_2 cost of walking, the VO_2 rate was normalized to the distance traveled (VO_2 cost = VO_2 rate/self-selected walking velocity). Significant differences were found in VO_2 cost (ANOVA, $p < 0.0001$), with the Tukey method showing that the transfemoral and hip disarticulation groups had a greater VO_2 cost than the control subjects and those with a Syme, transtibial, or knee disarticulation amputation level. Significant differences were seen in self-selected walking velocity (ANOVA, $p < 0.0001$), with the Tukey method showing that the transfemoral group walked significantly more

TABLE III Metabolic Data Collected During Walking for the Children with a Unilateral Amputation Presented as a Percentage of Control Values for Comparison Across Age Groups

	Syme Amputation* (%)	Transtibial Amputation* (%)	Knee Disarticulation* (%)	Transfemoral Disarticulation* (%)	Hip Disarticulation* (%)	P Value (ANOVA)
Resting						
VO_2 rate *(mL/kg/min)*	113† ± 31	103 ± 28	97 ± 14	85 ± 15	105 ± 18	0.0979
Heart rate *(bpm)*	96 ± 14	95 ± 16	94 ± 12	100 ± 13	100 ± 22	0.6725
Walking						
VO_2 rate *(mL/kg/min)*	97 ± 25	104 ± 14	111† ± 19	116 ± 23	111 ± 30	0.1303
VO_2 cost *(mL/kg/m)*	105 ± 25	110 ± 18	122 ± 14	151 ± 31	161 ± 55	<0.0001‡
Velocity *(m/min)*	95 ± 13	97 ± 8	92 ± 10	80 ± 13	72 ± 14	<0.0001§
Heart rate *(bpm)*	103 ± 13	105 ± 16	107 ± 19	117 ± 12	124 ± 21	0.0040#

*The values are given as the mean and standard deviation. †Significantly greater than the control. ‡The values in the Syme, transtibial, knee disarticulation, and control groups were significantly lower than those in the transfemoral and hip disarticulation groups. §The value in the transfemoral group was significantly lower than those in the Syme, transtibial, and control groups. The value in the hip disarticulation group was significantly lower than those in the Syme, transtibial, and knee disarticulation groups. #The value in the hip disarticulation group was significantly greater than those in the Syme and control groups.

TABLE IV Metabolic Data for the Unilateral and Bilateral Below-the-Knee Amputation Groups Presented as a Percentage of Control Values for Comparison Across Age Groups

	Unilateral Below-the-Knee Amputation* (N = 42) *(%)*	Bilateral Below-the-Knee Amputation* (N = 7) *(%)*	P Value (T Test)
Resting			
VO_2 rate *(mL/kg/min)*	110 ± 30	95 ± 36	0.1493
Heart rate *(bpm)*	96 ± 14	112 ± 20	0.0210
Walking			
VO_2 rate *(mL/kg/min)*	99 ± 22	94 ± 13	0.7895
VO_2 cost *(mL/kg/m)*	106 ± 23	111 ± 23	0.3012
Velocity *(m/min)*	95 ± 12	87 ± 11	0.0038†
Heart rate *(bpm)*	104 ± 14	119 ± 7	0.0006‡

*The values are given as the mean and standard deviation. †The value in the bilateral group was significantly lower than those in the unilateral and control groups. ‡The value in the bilateral group was significantly greater than those in the unilateral and control groups.

slowly than the Syme, transtibial, and normal groups, while the hip disarticulation group walked significantly more slowly than the Syme, transtibial, and knee disarticulation groups. The heart rate in the hip disarticulation group was significantly greater than that in the Syme and control groups (ANOVA, p = 0.0040).

Bilateral Amputation Group

The bilateral amputation group included five patients with a bilateral Syme amputation and two with a bilateral transtibial amputation (i.e., all below the knee). All patients in the bilateral group were able to complete the ten-minute walk at the self-selected velocity. To compare the patients with a unilateral below-the-knee amputation with those who had a bilateral (below-the-knee) amputation, we combined the patients with a unilateral Syme amputation and those with a transtibial amputation to create a group of forty-two patients with a unilateral amputation and intact knees (the unilateral below-the-knee amputation group) and compared them with the bilateral group.

The t test did not demonstrate a significant difference when it was used to compare the anthropometric means of the unilateral below-the-knee group and the bilateral below-the-knee group (body mass, p = 0.4654; body-mass index, p = 0.3324) or to compare the resting VO_2 rates of the two groups (p = 0.1493). In contrast, the resting heart rate was significantly

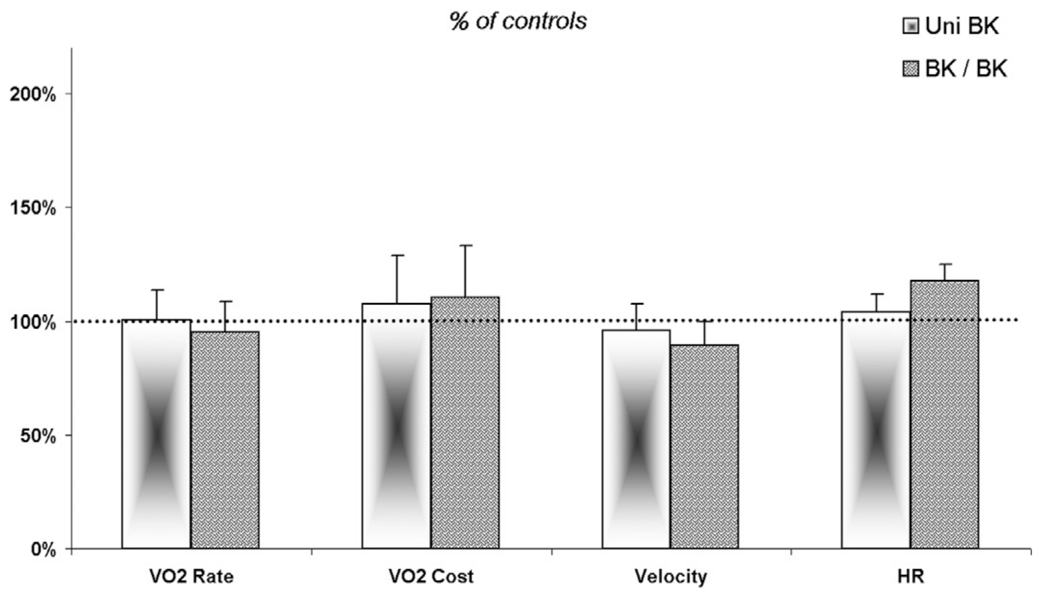

Fig. 2

Energy efficiency (and standard deviation), during walking, of children with a unilateral below-the-knee amputation (Uni BK) compared with that of children with a bilateral below-the-knee amputation (BK/BK) presented as a percentage of normal for comparison across age groups. HR = heart rate.

higher in the bilateral group than in the unilateral group ($p = 0.0210$). No significant differences were seen between the unilateral and bilateral groups with regard to the walking VO_2 rate or the VO_2 cost ($p = 0.7895$ and $p = 0.3012$, respectively) (Table IV and Fig. 2).

Compared with both the unilateral below-the-knee group and the control group, the bilateral group had a significantly slower mean self-selected walking velocity and a significantly higher mean heart rate (t test, $p = 0.0038$ and $p = 0.0006$, respectively) (Table IV and Fig. 2).

Discussion

Oxygen consumption during overground walking has been well documented in clinical populations, as well as in the normal population. It has been well established that adults with various levels of amputations walk more slowly and with a greater cost than their peers[19]. It has been unclear if this is the case for the pediatric population.

The results presented in this study show that the rate of oxygen consumption by children with a unilateral amputation is maintained regardless of the amputation level and as compared with control values. However, the VO_2 cost (the VO_2 rate normalized to the distance traveled) is significantly affected when the amputation is above the knee, as was seen in the patients with a transfemoral amputation or hip disarticulation. A previous study showed the heart rate to be higher than normal in 58% of children with an amputation and within normal limits in 31% of such children, while walking speed was maintained by most of the patients[20]. Nearly 70% of the amputations in that series were below the knee (partial foot, Syme, or transtibial), which may account for the children's ability to maintain speed with the majority of the patients having a normal heart rate. The results presented in our current study show that nearly 76% of patients with a lower-level amputation (including Syme, transtibial, and even knee disarticulation amputations) demonstrate an oxygen cost, heart rate, and walking velocity that are not significantly different from normal.

Differences in methodology may play a role in the inconsistency between our finding that VO_2 cost is not increased in children with a transtibial amputation and a previous report of a 15% increase in VO_2 cost[22]. In the previous study, the patients were tested while walking at a self-selected velocity on a treadmill, while our patients walked overground at a self-selected velocity. It may be that the conflicting findings of the two studies are due to the belt mechanics of the treadmill versus self-propulsion[25] during overground walking. In fact, it was shown that a very motivated patient with a transfemoral amputation could not sustain, during a treadmill protocol, a self-selected walking velocity that the subject had established during overground walking[12]. It is possible that children with an amputation must work harder to maintain a self-selected walking speed on a treadmill than they do during overground walking and that that explains the higher VO_2 cost during walking reported in the previous reports.

In a comprehensive study of energy efficiency in adults with an amputation, Waters et al. concluded that increases in VO_2 cost depended on the level of amputation[1]. The trend for the VO_2 cost to increase as the level of amputation ascends the lower limb in adults was mimicked by our pediatric data (Fig. 3); however, the differences did not become significant in the pediatric population until the amputation was above the knee. The children with a Syme, transtibial, or knee disarticulation amputation were able to maintain a nearly normal walking speed (95%, 97%, and 92% of normal, respectively) without significantly increasing the cost of walking (105%, 110%, and 122% of normal, respectively). In comparison, in the study by Waters et al., the adults with a Syme or transtibial amputation due to vascular disease walked at 66% and 55% of normal walking speed, at a VO_2 cost of 131% and 163% of normal, all of which values were significantly different from normal[1]. The adults with a traumatic below-the-knee amputation fared better, walking at a speed of 87% of normal with a VO_2 cost of 125% of normal.

In our group of children with a transfemoral amputation, VO_2 cost was 151% of normal while the self-selected walking velocity was 80% of normal. Both of these variables were significantly different from the control values and from those in the Syme, transtibial, and knee disarticulation groups. The increased VO_2 demand seen in the children with a transfemoral amputation (151% of normal) was nearly the same as that in the adults with a transfemoral amputation (156% of normal)[19]. The adults with a transfemoral amputation due to vascular disease fared much worse, having a VO_2 cost that was 219% of normal. While the children with a transfemoral amputation walked at 80% of the normal speed, the adults with a traumatic transfemoral amputation walked at 63% of normal walking velocity and the adults with a transfemoral amputation due to vascular disease, at a dismal 43%. The children with a transfemoral amputation were able to maintain a walking speed close to that of their peers, unlike either adult group.

In our study, children with a hip disarticulation walked at 72% of age-matched normal velocity, while the adults in a previous study walked at 63% of normal velocity[8]. The adults with a hip disarticulation had a VO_2 cost that was 143% of normal, while the children with such an amputation had a cost of 161%. The children with a hip disarticulation managed to walk nearly 10% faster, at a higher energy cost, than the adults with that amputation. The five children with a hip disarticulation included in our series used a prosthesis as their primary mode of walking, unlike the adult population, who commonly shed their prosthesis for the more energy-efficient crutch mobility[8].

In a previous study, six older adults who had undergone a bilateral below-the-knee amputation because of vascular disease walked at 64% of normal speed with a VO_2 cost of 223% of normal[4]. Waters and Mulroy reported that patients with a traumatic bilateral below-the-knee amputation walked at 82% of normal speed, with a VO_2 cost that was 125% of normal[19]. The children with a bilateral below-the-knee amputation in our study walked at similar speed (87% of normal) with a slightly lower VO_2 cost (111% of normal). Not surprisingly, the children walked far more efficiently than the adults with an amputation due to vascular disease and more like the adults with a

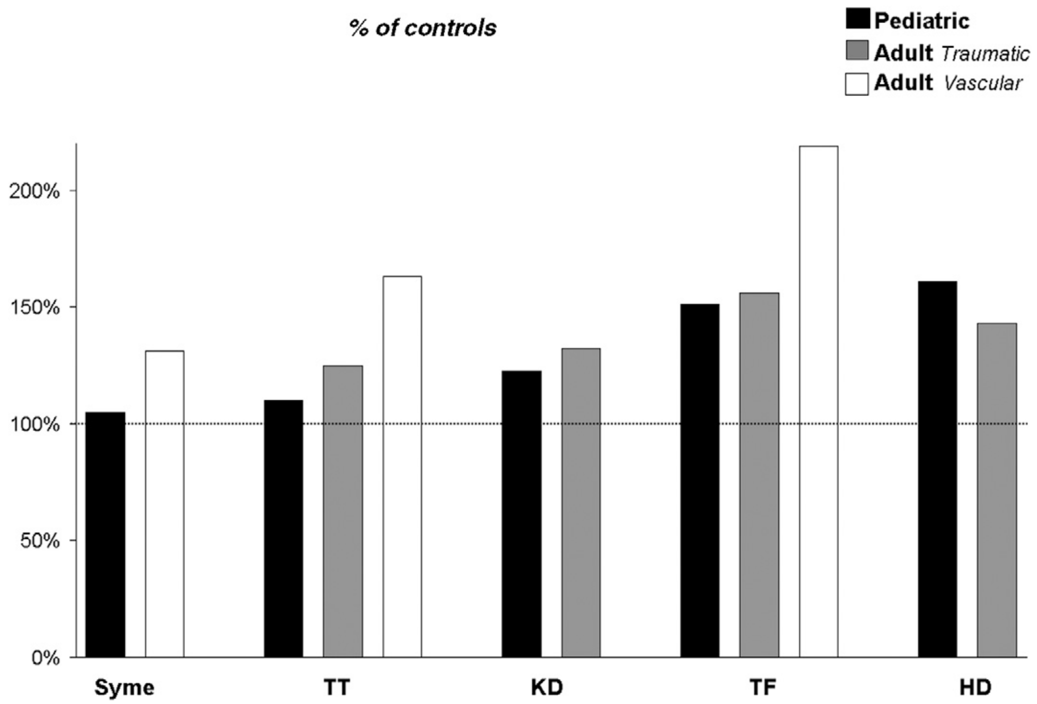

Fig. 3

VO_2 cost, during walking, of children and adults with an amputation presented as a percentage of normal for comparison across age groups. The data for the adults with a vascular-disease-related or traumatic Syme, transtibial (TT), knee disarticulation (KD), or transfemoral (TF) amputation[1] and those for the adults with a hip disarticulation (HD)[8] were obtained from the literature.

traumatic amputation. This comparison makes it easy to see how much of an impact vascular disease has on gait following an amputation.

Having normative data on children, of all ages, with an amputation has proven useful in our clinical practice. Clinicians including prosthetists, physical therapists, and orthopaedic surgeons have all had the opportunity to use our growing database as a reference for patient care, whether it be gait analysis to help in prosthetic alignment or the assessment of the energy cost of walking for a young patient with a hip disarticulation. Using quantitative data as a learning tool to better understand all forms of walking efficiency not only has proven to be a helpful way of providing our clinicians with more detailed information about the patients whom they are treating but also has given us an appreciation for how children with limb differences compare with their peers. We have found that a multidisciplinary approach is useful in caring for and assessing our pediatric amputation population.

It should be noted that the data for this study were collected in a laboratory, in a controlled setting. Patients were allowed to self-select their walking speed, and each lap was monitored for consistency. These are not the conditions most people encounter in their daily life, and this is a limitation of the study. Walking at a self-selected speed is not a particularly challenging activity for most children with a Syme, transtibial, or knee disarticulation amputation and does not require them to perform outside their preferred comfort zone. The use of a treadmill, where speed and incline can be manipulated to increase the metabolic demand during exercise, may help to better distinguish between groups. Another way of looking at daily activity and function is using a step activity monitor, with which data can be collected over a number of days and actual activity in "normal everyday life" can be assessed. Both of these modes of assessing function are worth further consideration and provide ideas for future work.

In summary, children with a Syme, transtibial, knee disarticulation, or bilateral below-the-knee amputation walk essentially as fast as their normal peers, without increasing their energy cost of walking. Children with an amputation level above the knee walk more slowly and at a greater energy cost, but all such children in our study chose to utilize a prosthesis for walking. We concur with Waters et al.[1] that an amputation should be done at the lowest possible level[1], even in children. ■

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