PROSTHETICS/ORTHOTICS/DEVICES

Oxygen Consumption During Ambulation: Comparison of Using a Prosthesis Fitted With and Without a Tele-Torsion Device

John G. Buckley, PhD, Steven F. Jones, BSc, Karen M. Birch, PhD

ABSTRACT. Buckley JG, Jones SF, Birch KM. Oxygen consumption during ambulation: comparison of using a prosthesis fitted with and without a tele-torsion device. Arch Phys Med Rehabil 2002;83:576-81.

Objective: To determine the energy expenditure and subjective comfort rating of walking in transtibial amputee patients using their prosthesis fitted either with or without a tele-torsion device (TT Pylon).

Design: Randomized, before-after trial.

Setting: Gait laboratory.

Participants: Six men, moderately active, with unilateral transtibial amputation (mean age, 39.5 ± 9.9y).

Intervention: Subjects walked on a motorized treadmill using their prosthesis fitted either with (ProsWith) or without (ProsWithout) a TT Pylon. Trials were repeated with subjects walking at speeds 100%, 130%, and 160% of their "normal" pace.

Main Outcome Measures: The energy expended ($\dot{V}O_2$) and subjective comfort rating during each walking trial.

Results: $\dot{V}O_2$ during walking with the prosthesis fitted with the TT Pylon was 5.4% and 9.1% lower than when using the prosthesis without the TT Pylon, at the speeds 130% and 160% of normal, respectively. Findings at the speed 160% greater than normal were significant ($P < .05$). Two of the subjects perceived no difference in prosthetic comfort between ProsWith and ProsWithout. The other 4 subjects preferred the TT Pylon at all speeds.

Conclusion: Use of a TT Pylon can significantly reduce the energy expenditure of walking at speeds above normal.

Key Words: Artificial limbs; Limb prosthesis; Oxygen consumption; Rehabilitation; Walking.

THE ENERGY COST of ambulation has consistently been shown to be greater in individuals with a lower-limb amputation than in able-bodied individuals walking at comparable speeds.[1-7] The mechanisms for this increase have been suggested as being related to reduced comfort and a reduction in stance phase propulsion from the prosthetic limb, which results in compensatory limb function bilaterally and gait asymmetries.[8-11] Consequently, to minimize energy expenditure, the preferred walking speed of lower-limb amputee patients tends to be slower than their able-bodied counterparts.[2,7]

In an attempt to reduce the energy expenditure associated with amputee gait, developments in prosthetic design have aimed at improving amputee patients' comfort and increasing the propulsion generated from the prosthetic limb. Perhaps the most significant of these developments is the so-called energy-storing foot. Such devices use carbon fiber materials to create a foot with the ability to elastically deform on impact and subsequently recoil during terminal stance, thus providing help with forward propulsion. Although a number of studies found no significant reduction in the oxygen consumption of amputee patients who use these feet at normal, self-selected walking speeds,[8,12,13] research has generally indicated an improvement in comfort and a reduction in the energy cost of ambulation at speeds greater than an individual's normal pace.[1,6,12,14,15]

A prosthetic shin (with or without the use of an energy storing foot) that has the ability to elastically compress at impact is another development aimed at improving amputee comfort and may reduce the energy expended during ambulation by elastically recoiling at push off. The first reported use of a prosthesis that had controlled shortening of the shin segment during ambulation was in the 1980s. This specially designed transfemoral prosthesis allowed Terry Fox to travel, on foot, half-way across the expanse of Canada.[16] Since then, many commercial devices have been developed for use by transtibial and to a lesser extent, transfemoral amputee patients. One such device is the recently developed Endolite TT (tele-torsion) Pylon.[a]

The TT Pylon (fig 1) is a single device that is fitted into the shin of a patient's prosthesis and provides shock absorption by the use of a linear compression spring, which is selected according to the patient's weight and activity level. In absorbing the force of impact, the device compresses, shortening its length by up to 13mm during stance. Additionally, a torsional spring element is designed simultaneously to dampen axial torques in an attempt to reduce the shear effects at the stump-socket interface. Because the device can also elastically recoil during push-off, it is thought that it should not only improve amputee patients' comfort but should also reduce the energy cost of ambulation. Because the device can be fitted into a patient's existing prosthesis, it is also relatively inexpensive.

Given the problems associated with ambulation in amputee patients, any prosthesis that has the potential to reduce energy expenditure, while also improving amputee patients' comfort, is of great value to this population. Thus, the aim of this study was to determine the energy expenditure and subjective comfort rating of walking in transtibial amputee patients when using their prosthesis fitted either with or without a tele-torsion device.

METHOD

Participants

Six men with unilateral transtibial amputation (mean age, 39.5 ± 9.9y), who had lost their limb either traumatically (n =

From the Department of Exercise and Sport Science, Manchester Metropolitan University (Buckley, Jones, Birch), and Disablement Services Centre, Withington Hospital (Buckley), Manchester, UK.

Accepted in revised form April 30, 2001.

Reprint requests to John G. Buckley, PhD, Biomechanics Research Group, Dept of Exercise and Sport Science, Manchester Metropolitan University, Hassall Rd, Alsager, Stoke-on-Trent, ST7 2HL, UK, e-mail: *j.buckley@mmu.ac.uk*.

0003-9993/02/8304-6619$35.00/0
doi:10.1053/apmr.2002.30624

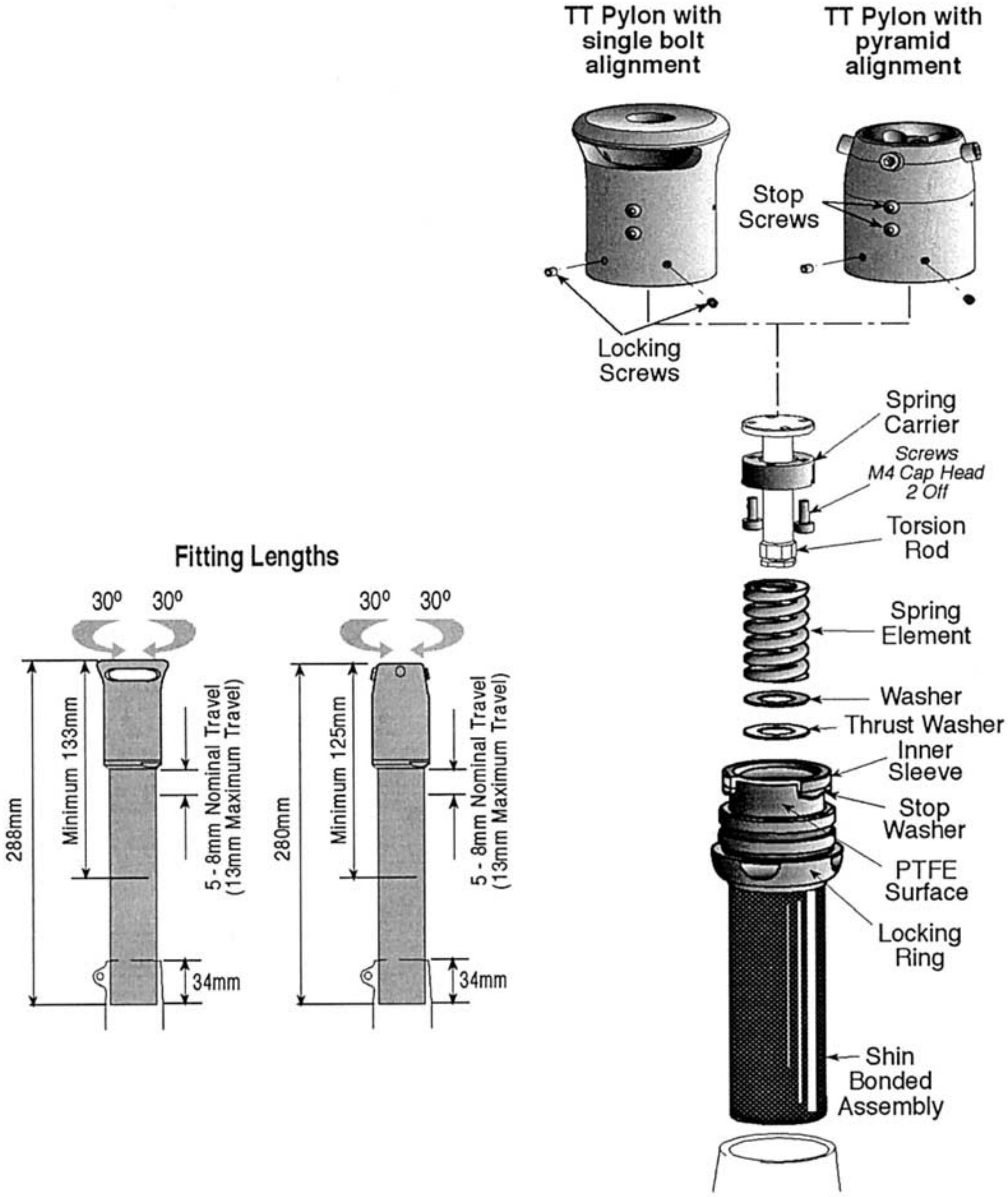

Fig 1. The TT Pylon with either single bolt or pyramid alignment. There are 3 categories of spring: 8kg/mm, 11kg/mm, and 14kg/mm. Spring choice is made according to the weight or activity level of the amputee patient. Nominal travel (compression) is between 5 and 8mm, and maximum travel is 13mm. The torsional rod allows a maximum of 30° rotation, either side of neutral, to occur. Abbreviation: PTFE, polytetrafluorethylene. © Charles A. Blatchfords and Sons, Ltd. Reprinted with permission.

5) or congenitally (n = 1), volunteered to participate in the study. Each subject gave informed consent, and the study met with local bioethics approval. All subjects self-reported that they were moderately active (undertaking exercise bouts of moderate intensity for at least 30min/d, 5d/wk), and all were able to complete the protocol in full with relative ease. Five of the subjects reported having no problems with their current prosthesis, whereas 1 subject (subject 4) indicated that he possessed an excessively loose-fitting socket but that he had been able to overcome this problem by wearing a number of sheaths over his residual limb to obtain a desired tighter fit. All subjects used total contact sockets with either an Iceross liner[b] and lanyard suspension or a sock into a standard expanded polyethylene foam liner. Subjects 1, 2, and 5 used a Dynamic Response Foot with a multiflex ankle.[c] Subject 3 used an Otto Bock C-Walk Foot,[d] subject 4 used a multiflex foot and ankle, and subject 6 used a SACH foot. (With perhaps the exception of the C-Walk Foot, none of these feet are regarded as high energy storing.) The prostheses of subjects 1, 2, and 5 were currently fitted with a TT Pylon. All subject characteristics are listed in table 1.

Table 1: Subject Data

Variable	Mean ± SD	Range
Age (y)	39.5 ± 9.9	28.0–52.0
Mass (kg)	84.8 ± 12.9	64.8–99.4
Height (cm)	173.1 ± 5.4	166.4–180.9
Stump length (cm)	15.5 ± 3.0	10.0–18.0
Years as amputee patient	15.2 ± 7.4	3.5–26.0
Years with current prosthesis	1.5 ± 0.4	1.0–2.0
Normal walking speed (km/h)	3.2 ± 0.3	2.9–3.6

Abbreviation: SD, standard deviation.

Pretest Protocol

On arrival at the laboratory, subjects were instructed to rest in the seated position for a period of 10 minutes. Resting heart rate, monitored by using a Polar™ Sports Tester PE400,[e] was recorded as the steady-state heart rate after this period of time. A period of test familiarization followed the seated rest. This required subjects to walk (wearing their usual prosthesis) on a motorized Ergo ELG 70 treadmill[f] with a 2.0 × 0.7m rubberized walking surface, until a normal gait was observed and subjects reported that they felt at ease. During this time, subjects were also familiarized to wearing the mouthpiece and nose clip that would be used during data collection.

To obtain an individually standardized walking speed, subjects were then asked to select the walking speed they perceived to be normal. Each subject was instructed to increase or decrease the speed of the treadmill until he/she felt this speed had been obtained. Normal was defined as the speed at which subjects were comfortable and felt to be customary. In this manner, the normal walking speed of each subject was determined on 3 consecutive occasions, with subjects receiving no feedback on their selected speed. To minimize the effects of fatigue, subjects took a short rest between each trial and did not proceed to the next trial until their heart rate had dropped to within 10% of their baseline level. Normal walking speed for each subject was recorded as the average of the 3 self-selected speeds. Because the usual prosthesis of half of the subjects was already fitted with a TT Pylon, 3 subjects' comfortable speed was determined by using their prosthesis fitted with a TT Pylon, whereas the other 3 subjects' speed was determined by using their prosthesis without a fitted TT Pylon.

For reasons of safety, subjects were required to wear a safety harness during any time spent on the treadmill. The harness, consisting of a shoulder girdle and a waist belt, was secured to a safety frame positioned immediately above the subject by a length of rope. At the sight of attachment to the safety frame, a cut-out mechanism ensured that when excessive tension was applied to the rope (eg, if a subject was to stumble or fall), the treadmill would automatically stop. Subjects were told of this safety mechanism and were also informed that the rope and harness would support their weight, if they should stumble. On questioning, each subject reported no distress or discomfort while walking on the treadmill.

Test Protocol

Two prosthetic limb types were used during testing: the subject's usual prosthesis either fitted with (ProsWith) or without (ProsWithout) a TT Pylon. After a rest period of approximately 15 minutes, subjects walked using each prosthesis at 3 ambulatory speeds: their normal walking speed (NW), 130% of their normal speed (130NW), and 160% of their normal speed (160NW). To counter any potential order effects, the performance of these ambulatory speeds was randomized. Because the usual prosthesis of half of the subjects was already fitted with a TT Pylon, it was deemed unnecessary to randomize the order of which limb type to test first. Thus, the first 3 walks were completed with subjects using their usual prosthesis. The fitting and alignment of the nonusual prosthesis to all 6 subjects was performed by a fully qualified and experienced prosthetist. The fitting and alignment of the subject's usual prosthesis had already been performed by a professional health service prosthetist. Because the only difference between the 2 test conditions was the inclusion of a TT Pylon into the shin of each subject's prosthesis, an extended familiarization period was deemed unnecessary. Thus, after each subject's prosthesis had been altered by either fitting or deactivating the TT Pylon, they were only given 5 to 10 minutes in which to familiarize themselves with walking with the altered prosthesis.

To eliminate potential fatigue effects, subjects undertook a period of rest between each ambulatory level. The period of rest followed the same criteria as set out during the determination of NW; ie, subjects did not proceed to the next ambulatory condition until their heart rate had dropped to within 10% of their previously recorded baseline level. For all subjects, this occurred relatively quickly (within 5min) after trials at NW. However, after trials at the higher walking speeds, some patients required as much as a 10- to 15-minute rest period.

Each ambulatory level required the subject to walk on the treadmill (0° inclination) for a period of approximately 6 minutes. Expired air was collected for analysis after each subject had walked for at least 3 minutes and had achieved a steady state. A steady state of exercise was deemed to have occurred when minute variation in heart rate was less than ±6 beats/min (American College of Sports Medicine Guidelines[17]). Subjects were handed a mouthpiece that was connected to a Douglas bag by a gas collection tube and a nose clip and were instructed to position these as previously shown. Two minutes of expired air was subsequently collected for future analysis. Each subject's perception of prosthetic comfort was assessed at the 5-minute mark of ambulation by using a 5-level perceived comfort scale. This scale was anchored from 1 (very comfortable) to 5 (very uncomfortable).

Gas Analysis

Gas analysis was performed by using the Servomex 1400 Series paramagnetic/infrared gas analyzer.[g] After calibrating the gas analyzer, the fraction of expired oxygen and the fraction of expired carbon dioxide were determined for each Douglas bag by drawing expired air through the gas analyzer for a period of exactly 1 minute. Minute volume and the temperature of the expired air remaining in the Douglas bag were determined by drawing it through a Harvard dry gas meter[h] and across an Edale thermometer.[i] Linearity of the dry gas meter had been previously checked against a 3-L precision gas calibration syringe.[j] The volume of oxygen consumption ($\dot{V}O_2$) at each ambulatory speed was calculated by using standard procedures. The ambient pressure, ambient temperature, and relative humidity during testing averaged 762.8 ± 4.7mmHg, 20.2° ± 1.2°C, and 33.7% ± 0.5%, respectively. All gas volumes were corrected to standard, temperature, and pressure dry.

Statistical Analyses

Because of the small sample size, nonparametric statistical tests were used for the analysis of the results. The $\dot{V}O_2$ recorded during walking in the ProsWith and ProsWithout conditions was compared at each of the walking speeds by using 1-tailed Wilcoxon signed-rank tests. For both conditions (separately), the $\dot{V}O_2$ recorded at each speed was compared by using a repeated-measures Friedman analysis of variance. Post hoc analysis for these tests was performed by using Wilcoxon signed-rank tests. Level of significance was set at $P \leq .05$. All statistical analyses were undertaken by using STATISTICA, version 5.1[k] for Windows.

To provide a subjective evaluation of the comfort provided by the prosthesis fitted with or without the TT Pylon, each subject's perceived prosthetic comfort rating was plotted on a visual scale for each ambulatory speed. A group mean perceived comfort rating was also determined (lowest mean score indicating the group's preference) for each ambulatory speed.

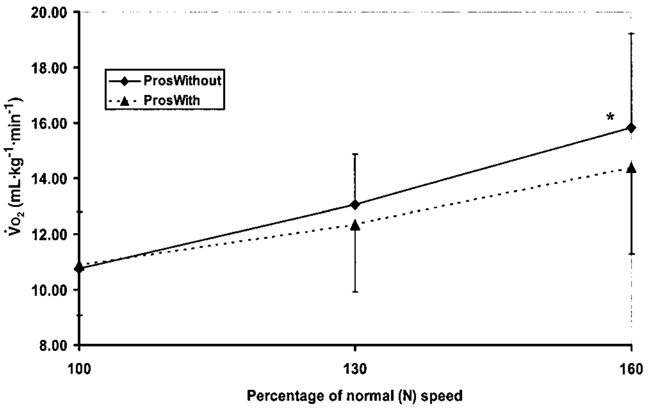

Fig 2. Oxygen uptake (mean $\dot{V}O_2$) when using prosthesis fitted with or without TT Pylon.* Difference between prosthetic limb type was significant ($P = .05$).

RESULTS

The mean NW for the group was 3.2 ± 0.3km/h (range, 2.9–3.6km/h); thus, 130NW and 160NW were 4.2 ± 0.4km/h and 5.1 ± 0.6km/h, respectively. Figure 2 shows the mean $\dot{V}O_2$ recorded while using each prosthesis for each of the 3 ambulatory speeds, whereas the individual data is in table 2. As ambulatory speed increased, $\dot{V}O_2$ increased significantly ($P < .05$), for both ProsWith and ProsWithout conditions.

As speed increased, the $\dot{V}O_2$ recorded when subjects used their prosthesis fitted with the TT Pylon was, for the most part, less than when the prosthesis was used without. There was no difference ($P > .05$) in the $\dot{V}O_2$ recorded during walking with or without the TT Pylon at NW. The magnitude of the $\dot{V}O_2$ reduction for ProsWithout compared with ProsWith was 5.4% and 9.1%, for the ambulatory speeds at 130NW (ProsWith, 12.35 ± 2.42mL · kg^{-1} · min^{-1}, ProsWithout, 13.06 ± 1.80 mL · kg^{-1} · min^{-1}) and 160NW (ProsWith, 14.4 ± 3.12 mL · kg^{-1} · min^{-1}, ProsWithout, 15.8 ± 3.40mL · kg^{-1} · min^{-1}), respectively. However, the $\dot{V}O_2$ was only significantly lower ($P < .05$) at the 160NW. There was no interaction of speed and prosthesis ($P > .05$).

Table 3 indicates the perceived prosthetic comfort rating for each ambulatory speed for each subject separately. Subjects 1, 2, 5, and 6 favored the TT Pylon for all speeds. Subjects 3 and 4 perceived no difference in prosthetic comfort between ProsWith and ProsWithout. The mean perceived comfort score for subjects using the ProsWith remained constant at 1.33 ± .52 across all speeds. The mean perceived comfort score for subjects using the ProsWithout was 2.17 ± .75, 2.17 ± .75, and 2.5 ± 1.22 for the ambulatory speeds NW, 130NW, and 160NW, respectively.

DISCUSSION

One of the more important considerations in the design and prescription of lower-limb appliances, which facilitate or assist ambulation, is the level of energy expenditure that will be required when using the device. The aim of our study was to compare the energy expended (and subjective rating) during walking in transtibial amputee patients using their existing prosthesis fitted either with or without a tele-torsion device. Results showed that use of the TT Pylon reduced the $\dot{V}O_2$ measured during walking, by 5.4% and 9.1%, at speeds representing 130% and 160% of self-selected normal (normal mean, 3.2 ± 0.3km/h), respectively, with only the difference at the fastest speed being significant ($P < .05$). There was no difference ($P > .05$) in the $\dot{V}O_2$ recorded during walking with or without the TT Pylon at normal walking pace.

Because the only difference between the 2 walking conditions was the inclusion of a TT Pylon into each subject's prosthesis, it would be convenient to attribute the energy savings found solely to the mechanical function of the TT Pylon. However, it is possible that the benefits determined were also caused by the TT Pylon altering the function of the existing prosthetic components; eg, the dynamic function of the subject's artificial foot may have improved when the TT Pylon was fitted. Future work investigating the benefits of using a TT Pylon should take into account this possibility. Interestingly, the 3 subjects (subjects 1, 2, 5) who seemed to benefit the most from using the TT Pylon were the experienced users of the device (they also all used a Dynamic Response Foot). This indicates that an individual has to learn how to use the TT Pylon effectively; this suggests that its use alters the mechanics of gait (eg, ankle or knee function) appreciably. It also indicates that future work should allow an extended familiarization period after modification of a subject's prosthesis.

The findings presented here are similar to those of Nielsen et al[6] and Hsu et al,[18] who reported $\dot{V}O_2$ during walking to be lower when subjects used either a FlexFoot[l] or Re-Flex-VSP[l] (both so-called energy-storing feet) compared with a conventionally designed foot (SACH) at speeds above self-selected normal. At walking speeds 4.0 and 4.8km/h, which are similar to the higher speeds used in our study (4.2, 5.1km/h), Hsu[18] reported a reduction in $\dot{V}O_2$ of 4% and 5%, respectively, while using a Re-Flex-VSP. The magnitude of this difference is similar to that of our study, which suggests that the use of a TT Pylon may provide an equivalent reduction in the energy expenditure of walking. It is well known that the energy cost of ambulation per meter is greater in older transtibial amputee patients (usually vascular amputation) than in younger trans-

Table 2: Individual $\dot{V}O_2$* During Walking When Using Prosthesis With (ProsWith) and Without (ProsWithout) TT Pylon

	Normal Speed		130% of Normal		160% of Normal	
Subject	ProsWithout	ProsWith	ProsWithout	ProsWith	ProsWithout	ProsWith
1	12.45	11.91	13.56	11.92	17.12	14.60
2	13.89	13.89	15.98	16.40	21.19	19.85
3	8.85	8.65	11.27	9.00	10.76	11.58
4	10.59	10.12	11.18	12.02	14.92	11.92
5	9.11	10.00	12.60	11.57	14.88	12.69
6	9.74	10.82	13.78	13.19	16.17	15.75
Mean	10.77	10.90	13.06	12.35	15.84	14.40
SD	2.00	1.81	1.80	2.42	3.40	3.12

* $\dot{V}O_2$ as mL · kg^{-1} · min^{-1}.

Table 3: Subjective Measures of Perceived Prosthetic Comfort at Each of the Ambulatory Speeds

Level of Perceived Comfort	Subject 1		Subject 2		Subject 3		Subject 4		Subject 5		Subject 6	
	Without	With	Without	With	Without	With	Without	With	Without	With	Without	With
Very comfortable				● * ◆	● * ◆	● * ◆				● * ◆		● * ◆
Comfortable		● * ◆	● * ◆				● * ◆	● * ◆			● * ◆	
Mild discomfort	● *								● *			
Discomfort	◆								◆			
Very uncomfortable												

Abbreviation: Without, without TT Pylon; With, with TT Pylon; ●, normal speed; *, 130% of normal speed; ◆, 160% of normal speed.

tibial amputee patients (usually traumatic amputations).[19] In an attempt to reduce the energy cost of ambulation, individuals with vascular transtibial amputation tend to walk at a slower customary walking speed. For these individuals, who make up the majority of the transtibial amputee patient population, the use of a device that can reduce the energy cost of walking at speeds greater than normal may have limited appeal. In contrast, for younger traumatic transtibial amputee patients, who desire and can achieve a range of walking speeds, the benefit of using such a device may be high.

An individual's self-selected normal speed (as a function of step rate and length) is typically the most economical.[20] It, therefore, follows that the speed chosen as the most economical is (among other factors) the one that minimizes the work done at the joints of the lower extremity during ambulation. The use of an energy-storing (and releasing) device (eg, Re-Flex-VSP or TT Pylon) is thus unlikely to make much difference to the energy expended during walking because the power output required from the limb, at this speed, is minimal. This would explain why previous studies[8,12,13] found no significant physiologic benefit when energy-storing feet at the subjects' normal walking speed were used. Although our study also found no significant difference in $\dot{V}O_2$ when subjects walked at their self-selected normal pace, using their prosthesis fitted either with or without the TT Pylon, 4 of the 6 subjects perceived an improvement in comfort when their prosthesis was fitted with the TT Pylon. Thus, the benefit of using a TT Pylon at normal speed might well be that subjects feel they are able to walk for longer without experiencing discomfort and are able to do so with no increase in the $\dot{V}O_2$ from that required when using the prosthesis without the device. Thus, long-term use of a TT Pylon may bring about an increase in an individual's customary walking speed. Future work of a longitudinal nature and of a large sample size are required to confirm this.

To explain the mechanisms for the lower $\dot{V}O_2$ observed using so-called energy-storing feet, a number of studies have determined the mechanical power output at the joints of the lower extremity.[1,11,21] This approach not only provides insight into the biomechanical adaptations used by amputee patients to compensate for the reduced motor function resulting from amputation and prosthetic replacement but can also be used to determine the power absorbed and generated (released) by the prosthetic foot. Findings show that compared with a SACH foot, the use of an energy-storing foot increases both the energy absorbed and generated at the prosthetic ankle. This provides some insight into why $\dot{V}O_2$ is lower during walking when using an energy-storing foot. However, as their use does not significantly reduce the compensatory power output seen at the knee and hip, this does not fully explain the observed reduction in energy expenditure. In our study, subjects used their prosthesis either fitted with or without a TT Pylon, while the prosthetic foot remained constant; thus the alteration in $\dot{V}O_2$ cannot be directly attributed to improved prosthetic foot function. Future work is therefore needed to determine the mechanical factors involved in using a prosthesis incorporating a shank with telescopic properties. Rather than determine the power at the joints of the lower extremity, such work could perhaps determine changes in the energy of the center of mass or changes in the stiffness of the prosthetic limb, when fitted with such a device. Because recent work[22,23] investigating what determines vertical displacements of the body during walking has suggested that pathologic gaits may be improved by controlling vertical excursions of the body, such an approach certainly warrants consideration. It may well be that the reduced $\dot{V}O_2$, measured while walking using the TT Pylon, resulted from reduced, or better controlled, vertical elevation of the subject's center of mass as a consequence of altered limb stiffness. This may also explain why most subjects perceived more comfort when using the TT Pylon.

CONCLUSION

The results of our study indicate that inclusion of a TT Pylon into the prosthesis of a group of transtibial amputee patients resulted in a reduction in the $\dot{V}O_2$ measured when subjects walked at speeds 130% and 160% greater than normal. The reduction in $\dot{V}O_2$ at the speed 160% greater than normal was significant ($P < .05$). With only 6 subjects, the findings of this study should be viewed as preliminary. Findings will need to be corroborated by studies on a larger scale before the benefits (or otherwise) of using a tele-torsion device can be confirmed.

Acknowledgments: We thank Chas A. Blatchford & Sons Ltd, Basingstoke, Hampshire, UK, for supplying the prosthetic components used during testing and Joseph R. McCarthy of Chas A. Blatchford & Sons for making prosthetic alterations during the testing.

References

1. Colborne GR, Naumann S, Longmuir PE, Berbrayer D. Analysis of mechanical and metabolic factors in the gait of congenital below knee amputees. A comparison of the SACH and Seattle foot. Am J Phys Med Rehabil 1992;71:272-8.
2. Waters RL, Yakura JS. The energy expenditure of normal and pathological gait. Crit Rev Phys Rehabil Med 1989;1:183-209.
3. Pagliarulo MA, Waters R, Hislop H. Energy cost of walking of below knee amputees having no vascular decease. Phys Ther 1979;59:538-43.
4. Waters RL, Perry J, Antonelli D, Hislop H. Energy cost of walking of amputees: the influence of level of amputation. J Bone Joint Surg Am 1976;58:42-6.
5. Huang CT, Jackson JR, Moore NB, Fine PR, Kuhlemeier KV, Traugh GH. Amputation: energy cost of ambulation. Arch Phys Med Rehabil 1979;60:19-24.
6. Nielsen DH, Shurr DG, Golden JC, Meier K. Comparison of energy cost and gait efficiency during ambulation in below knee amputees suing different prosthetic feet—a preliminary report. J Prosthet Orthot 1988;1:24-31.
7. Fisher SV, Gullickson G. Energy cost of ambulation health and disability: a literature review. Arch Phys Med Rehabil 1978;59:124-33.

8. Lehmann JF, Price R, Boswell-Bessete S, Dralle A, Questad K, deLateur BJ. Comprehensive analysis of energy storing prosthetic feet: Flex foot and Seattle foot versus standard SACH foot. Arch Phys Med Rehabil 1993;74:1225-31.
9. Winter DA, Sienko SE. Biomechanics of below-knee amputee gait. J Biomech 1988;21:361-7.
10. Hurley GR, McKenny R, Robinson M, Zadravee M, Pierrynowski MR. The role of the contralateral limb in below knee amputee gait. Prosthet Orthot Int 1990;14:33-42.
11. Czerniecki JM, Gitter AJ. Gait analysis in the amputee: has it helped the amputee or contributed to the development of improved prosthetic components? Gait Posture 1996;4:258-68.
12. Casillas J, Dulieu V, Cohen M, Marcer I, Didier J. Bioenergetic comparison of new energy-storing foot and SACH foot in traumatic below knee vascular amputations. Arch Phys Med Rehabil 1995;76:39-44.
13. Torburn L, Powers C, Guiterrez R, Perry J. Energy expenditure during ambulation in dysvascular and traumatic below-knee amputees: a comparison of five prosthetic feet. J Rehabil Res Dev 1995;32:111-9.
14. Wagner J, Sienko S, Supan T, Barth D. Motion analysis of SACH versus Flex-Foot in moderately active below-knee amputees. Clin Prosthet Orthot 1987;11:55-62.
15. Wing D, Hittenberger D. Energy-storing prosthetic feet. Arch Phys Med Rehabil 1989;70:330-5.
16. DiAngelo DJ, Winter DA, Ghista DN, Newcombe WR. Performance assessment of the Terry Fox jogging prosthesis for above-knee amputees. J Biomech 1989;22:543-58.
17. American College of Sports Medicine. ACSM's resource manual for guidelines for exercise testing and prescription. 3rd ed. Philadelphia: Williams & Wilkins; 1998.
18. Hsu M, Neilsen DH, Yack HJ, Shurr DG. Physiological measurements of walking and running in people with transtibial amputations with 3 different prostheses. J Orthop Sports Phys Ther 1999;29:526-33.
19. Water RL, Mulroy S. The energy expenditure of normal and pathologic gait. Gait Posture 1999;9:207-31.
20. Astrand P, Rodahl K. Textbook of work physiology. Physiological bases of exercise. 3rd ed. New York: McGraw-Hill; 1986.
21. Gitter A, Czerniecki JM, DeGroot DM. Biomechanical analysis of the influence of prosthetic feet on below-knee amputee walking. Am J Phys Med Rehabil 1991;90:142-8.
22. Gard SA, SD Childress. The influence of stance-phase knee flexion on the vertical displacement of the trunk during normal walking. Arch Phys Med Rehabil 1999;80:26-32.
23. Gard SA, Childress SD. What determines vertical motion of the body during normal gait? [abstract]. Gait Posture 2000;11:125-6.

Suppliers

a. Chas A Blatchford & Sons Ltd, Lister Rd, Basingstoke, Hampshire RG22 4AH, UK.
b. Iceross Liner Ossur, Grjothals 5, 110 Reykjavik, Iceland.
c. Endolite North America, 105 Westpark Rd, Centerville, OH 54559.
d. Otto Bock Health Care, 3000 Xenium Ln N, Minneapolis, MN 55441.
e. Polar Electro Oy, Professorintie 5, FIN 90440 Kempele, Finland.
f. Woodway USA, W229 N 591 Foster Ct, Waukesha, WI 53186.
g. Servomex Group Ltd, Jarvis Brook, Crowborough, East Sussex, UK.
h. Harvard Apparatus Ltd, Fircroft Way, Edenbridge, Kent TN8 6HE, UK.
i. Grant Instruments (Cambridge) Ltd, Shepreth, Cambridgeshire SG8 6GB, UK.
j. Hans, Rudolph Inc, 7200 Wyandotte, Kansas City, MO 64114.
k. StatSoft Inc, 2300 E 14th St, Tulsa, OK 74104.
l. Flex-Foot Inc, 26412-A Laguna Hills, Aliso Viejo, CA 92656.