Running-Specific Prostheses Permit Energy Cost Similar to Nonamputees

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ABSTRACT

BROWN, M. B., M. L. MILLARD-STAFFORD, and A. R. ALLISON. Running-Specific Prostheses Permit Energy Cost Similar to Nonamputees. *Med. Sci. Sports Exerc.*, Vol. 41, No. 5, pp. 1080–1087, 2009. Improvements in prosthesis design have facilitated participation in competitive running for persons with lower limb loss (AMP). **Purpose**: The purpose of this study was to examine the physiological responses of AMP using a run-specific prosthesis (RP) versus a traditional prosthesis (P) and cross-referenced with nonamputee controls (C) matched by training status, age, gender, and body composition during level treadmill running (TM). **Methods**: Twelve trained runners completed a multistage submaximal TM exercise during which HR and oxygen uptake ($\dot{V}O_2$) were obtained. Steady state measures at 134 $m{\cdot}min^{-1}$ were compared between RP and P in AMP. AMP using RP (AMP–RP) and C also performed a continuous speed-incremented maximal TM test until volitional fatigue. **Results**: RP elicited lower HR and $\dot{V}O_2$ compared with P in AMP. Using RP, AMP achieved similar $\dot{V}O_{2max}$ and peak TM speed compared with C but with higher HR_{max}. Relative HR ($\%HR_{max}$) and oxygen uptake ($\%\dot{V}O_{2max}$), the regression intercept, slope, SEE, and Pearson's r correlation were not different between AMP–RP and C. $\%HR_{max}$ calculated with the published equation, $\%HR_{max} = 0.73(\%\dot{V}O_{2max}) + 30$, was not significantly different from actual $\%HR_{max}$ for AMP–RP or C in any stage. **Conclusions**: RP permits AMP to attain peak TM speed and aerobic capacity similar to trained nonamputees and significantly attenuates HR and energy cost of submaximal running compared with a P. Use of RP confers no physiological advantage compared with nonamputee runners because energy cost at the set speed was not significantly different for AMP–RP. Current equations on the basis of the relative HR–$\dot{V}O_2$ relationship seem appropriate to prescribe exercise intensity for persons with transtibial amputations using RP.

Key Words: EXERCISE TESTING, LIMB LOSS, DISABLED SPORTS, FITNESS

In recent decades, prosthetic technology has improved to allow persons with lower limb loss (AMP) to participate in competitive running using running-specific prostheses (RP). The heel-less carbon J-shaped keel or "blade" of RP is designed to store elastic energy during the loading response phase of running, which is then released in the terminal stance phase (Fig. 1A). In contrast, a traditional prosthesis with rigid shank and incorporated ankle and heel component is less elastic than RP (Fig. 1B) (4). The traditional prosthesis generally does not permit fast running speeds; thus, competitive running was not feasible before the development of RP. Although prosthetic technology improvements have mainly been in the areas of materials and alignment, the knowledge base in biomechanics and physiological responses of persons with limb loss using these enhanced designs has been lacking. This has led to much speculation, controversy, and recent media attention related to the potential advantages that an RP might confer compared with a runner with intact limbs during competition (24,31).

Metabolic and biomechanical differences between AMP and nonamputee (C) walking gait have been studied extensively (10,11,15,19,37). The energy cost of walking for AMP can be up to 65% greater than C when walking at comparable velocities and/or preferred velocities. However, the differential in energy cost is variable (37) and may be related to the level of amputation (11,15,35,36), fitness level (19,33), cause of amputation (19), gait speed (7,12), and prosthetic properties (23,27,28,30). Previous investigations have examined energy return technology in prosthetic feet (generally called "dynamic response feet") and metabolic responses during ambulation (18,20,28). Compared to traditional prosthetic feet, dynamic response feet

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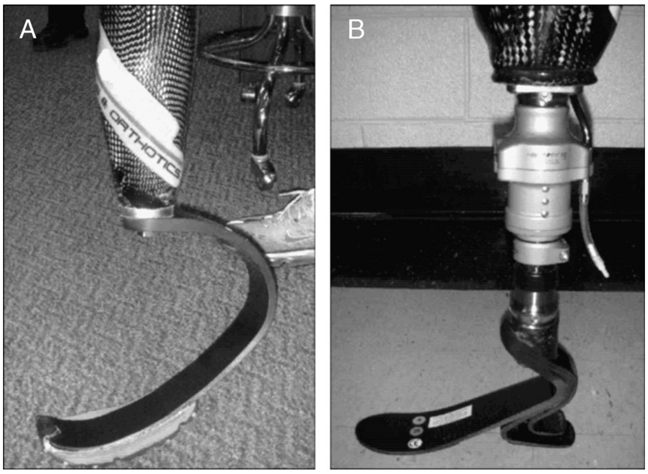

FIGURE 1—Lower limb prostheses worn by amputee subjects during running. A. J-shaped carbon keel or "blade" is characteristic of the running-specific prosthesis (RP). B. The non–running-specific "traditional" prostheses (P) used by all subjects had an energy return (dynamic response) foot design (shoe and foot shell removed for photograph).

are reported to reduce the energy cost of treadmill (TM) walking (18,28) and running (18). However, the impact of the more recent J-shaped RP, with energy return material properties extending beyond the dynamic response foot, has not been systematically examined concerning energy cost or physiological responses for running at various speeds.

Running forms the basis of many recreational activities and, ideally, is an ultimate objective in the complete rehabilitation of young, healthy AMP. For this population, however, little is known about typical physiological indicators such as HR that can translate into appropriate recommendations for exercise prescription (8). The American College of Sports Medicine (ACSM) recommends the minimal training intensity threshold to improve cardiorespiratory fitness is 50%–70% of maximal aerobic capacity ($\dot{V}O_{2max}$) or 70%–80% of maximal HR (HR_{max}) using the zero to peak method (1). This is based on the assumed linear relationship between HR and oxygen uptake ($\dot{V}O_2$) throughout graded exercise (1,25). However, exercise prescription developed on nonamputees might not directly transfer to AMP (8). Increased venous blood pooling from the absence of lower limb skeletal muscle pumps in paraplegics is thought to elevate submaximal HR relative to $\dot{V}O_2$ (17,29,32). How limb loss and residual limb muscle atrophy affects the HR–$\dot{V}O_2$ relationship in AMP is unclear but deserves further investigation to evaluate existing prediction equations and to develop new equations, if indicated (33).

Therefore, the purpose of this study was to compare physiological responses of AMP using RP (AMP–RP) versus traditional prosthesis (P) and matched nonamputee controls (C) during TM running and examine the relationship between HR and $\dot{V}O_2$ from submaximal to peak running speeds in AMP–RP versus C. Because the energy cost of running seems reduced with dynamic response prosthetic feet compared with traditional, less elastic feet (18,27), a running-specific prosthetic *leg* (RP) with energy return properties (extending beyond the foot) might effectively close the gap between AMP and C running energetics. We hypothesized that RP would lower oxygen uptake compared with P and minimize the difference in energy cost of running between AMP and C. Further, because of the potential impact of missing lower limb muscle mass on hemodynamics, it was hypothesized that HR relative to $\dot{V}O_2$ would be elevated in AMP compared with control subjects regardless of prosthesis.

METHODS

Subjects. Twelve (8 males and 4 females) runners participated in the study. All subjects performed run training (AMP subjects using RP) for a minimum of 4 h·wk^{-1} for at least 1 yr and competed regularly in running events. Subjects were unilateral transtibial (n = 5) and bilateral transtibial (n = 1) AMP due to nonvascular causes (trauma, n = 4; congenital, n = 1; bone cancer, n = 1). Five of the six AMP subjects were familiar with training on a TM. Control subjects were six age- and fitness-matched, nonamputee runners (C). Mean (±SD) physical characteristics are presented in Table 1. Informed written consent was obtained from all subjects as approved by the Institutional Review Board at the Georgia Institute of Technology.

Experimental Procedures. Subjects reported to the laboratory after a 3-h fast and having refrained from exercise and caffeine for 12 h before testing. AMP provided their own RP and P for all testing. A 24-h history questionnaire was completed to assess compliance with pretest instructions. Urine specimens were obtained before the test, and urine-specific gravity was measured with a handheld refractometer to ensure euhydration as evidenced by levels <1.021 (2). Anthropometric measurements were performed including height, weight, and lower limb lengths. For AMP, height and weight were determined with RP (as reported in Table 1) and also without prosthesis. For oxygen uptake measurements relative to body weight, the weight of the prosthesis used in the trial was factored into body weight. AMP residual limb length was measured from the greater trochanter to the distal end of noncompressed residual limb tissue. Body composition was measured using dual-energy x-ray absorptiometery (DEXA) Lunar Prodigy whole-body scanner (GE Medical Systems, Madison, WI).

TABLE 1. Mean (±SD) physical characteristics of amputee (AMP) and nonamputee (C) subjects (n = 12).

	AMP	C
Age (yr)	28.8 ± 7.3	29.5 ± 6.9
Height (cm)	176.8 ± 9.0	175.7 ± 5.6
Weight (kg)	70.4 ± 18.1	70.8 ± 15.0
% body fat	17.2 ± 6.7	17.9 ± 9.1
Residual limb length (% intact limb)	69.7 ± 6.9	N/A
Running volume (km·wk^{-1})	48.0 ± 22.4	48.0 ± 37.6

AMP wore no prosthetics during DEXA scanning. Fat-free mass (FFM) was calculated using percent of lean tissue multiplied by body weight without prosthesis.

After a 5-min warm-up at a self-selected pace, a discontinuous speed-incremented TM test was conducted using 0% grade throughout. The submaximal test protocol was designed to elicit an exercise intensity between 50% and 70% of $\dot{V}O_{2max}$. Control subjects ran the same submaximal TM protocol as their matched AMP. Five-minute run stages interspersed with 3-min rest periods were repeated until subjects reached 75% of age-predicted HR_{max} and/or an RPE of 15 (3). During rest periods, subjects remained standing on the TM while a blood sample was collected from the finger. All subjects ran two 134-m·min^{-1} (5-mph) stages, separated by a rest period that lasted until HR and $\dot{V}O_2$ returned to post–warm-up values (mean = 5.2 min). This replicate stage was performed in counterbalanced order for AMP using either P or RP. Immediately after the submaximal test, subjects performed a continuous, speed-incremented maximal TM protocol with 2-min run stages at 0% grade until volitional fatigue. AMP ran only in RP during the maximal TM test. Subjects initiated the maximal TM protocol using either the same speed as the last submaximal stage or a speed that was 13.4 m·min^{-1} (0.5 mph) greater. Thereafter, each subsequent stage was incremented by 13.4 m·min^{-1}. $\dot{V}O_{2max}$ was considered achieved at test termination on the basis of attainment of at least two of the following criteria: plateau in $\dot{V}O_2$ during the last two stages (increase <2.1 mL·kg^{-1}·min^{-1}), an HR within 10 beats·min^{-1} of age-predicted HR_{max}, RER ≥1.10, minute ventilation >115 L·min^{-1}, or blood lactate (BLa) >8 mmol·L^{-1}.

Measurements. $\dot{V}O_2$, as an indicator of energy cost, was obtained by open-circuit spirometry using a PARVO Medics TrueOne 2400 Metabolic Measurement System (Parvo Medics, Inc., Salt Lake City, UT). Resting energy consumption was measured during 5 min of standing on the TM before exercise testing. Exercise energy cost was determined using metabolic gases collected continuously during TM testing with $\dot{V}O_2$ and RER determined for each stage. HR was measured with telemetry (Polar Electro, Inc., Woodbury, NY). HR and RPE were recorded in the middle and last 30 s of each 5-min stage.

Statistical analysis. The sample size was estimated on the basis of previously published research with amputees versus controls, which showed a between-group $\dot{V}O_2$ difference of 2 mL·kg^{-1}·min^{-1} during TM walking with dynamic prosthetic feet (9,19). ANOVA with repeated measures (ANOVA–RM) was used to assess differences between AMP–RP and C for physiological responses during similar running speeds ranging from 134 to 241 m·min^{-1} (5–9 mph). Paired *t*-tests were used to compare AMP and matched C for descriptive anthropometric variables and peak physiological responses. Paired *t*-tests compared RP and P in AMP for physiological responses at the same absolute speed (134 m·min^{-1}). The association between relative HR (%HR_{max}) and relative energy cost (%$\dot{V}O_{2max}$) was analyzed with Pearson product–moment correlation. Individual linear regression equations describing the relative %HR_{max}–relative $\dot{V}O_2$ relationship were compared between actual and formula-predicted and between matched groups with *t*-tests. %HR_{max} values calculated for four relative intensities using individual linear regression equations were compared with ACSM's formula-calculated values with paired *t*-tests. In addition, actual %HR_{max} and predicted values for %HR_{max} (calculated using actual %$\dot{V}O_{2max}$ and the ACSM formula) were compared over all submaximal testing stages with ANOVA–RM. All statistical testing were conducted using SPSS (version 12.0; SPSS, Inc., Chicago, IL). An α level of 0.05 was used to indicate statistical significance. *Post hoc* power analyses were performed to determine partial ETa squared and observed power for all comparisons.

RESULTS

Peak physiological responses. Since $\dot{V}O_{2max}$ for AMP with P could not be accurately determined due to of the mechanical limitation to achieving a true peak TM run speed, for peak physiological values only comparisons between AMP–RP and C are reported. Table 2 illustrates values obtained during the maximal TM test for AMP–RP and C. AMP–RP achieved similar absolute $\dot{V}O_{2max}$, and $\dot{V}O_{2max}$ expressed relative to body weight and fat-free mass as C. Peak BLa and TM speed for AMP–RP were not statistically different than those for C, but there was a trend (P = 0.06) toward greater peak TM speed attained by C. HR_{max} in AMP–RP was higher ($P < 0.05$) by 8 beats·min^{-1} than in similarly aged C. The mean differential between age-predicted and actual HR_{max} was 7.2 ± 3.2 and 4.0 ± 5.5 beats·min^{-1} for AMP–RP and C, respectively.

Responses at the same absolute TM speed. As hypothesized, RP elicited significantly lower ($P < 0.05$) HR (by 13 beats·min^{-1} or 9%) and $\dot{V}O_2$ (by 5 mL·kg^{-1}·min^{-1} or 14%) compared with P in AMP during submaximal running at 134 m·min^{-1}. HR and $\dot{V}O_2$ for AMP using RP were not significantly different compared with matched C. However, AMP using P had significantly greater HR (by 15 beats·min^{-1}) and $\dot{V}O_2$ (by 8 mL·kg^{-1}·min^{-1}) compared with matched C (Fig. 2). Despite no significant difference between AMP–RP and C in mean HR (P = 0.085, observed power = 0.87), in five of the six matched pairs, HR for AMP–RP was higher than that for C (mean = +13%; ranging from +2% to 25%). RPE for AMP with P tended to

TABLE 2. Mean (±SD) peak physiological responses for amputees (AMP) wearing run-specific prostheses compared with matched controls C (n = 12).

	AMP	C
$\dot{V}O_{2max}$ (L·min^{-1})	3.90 ± 0.8	3.96 ± 0.9
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	56.3 ± 7.6	56.1 ± 7.3
$\dot{V}O_{2max}$ per FFM (mL·kg^{-1}·min^{-1})	69.4 ± 6.1	67.9 ± 4.4
HR_{max} (beats·min^{-1})	195.7 ± 6.6*	187.5 ± 4.6
Peak TM speed (m·min^{-1})	254.8 ± 32.2	278.9 ± 32.2
Peak BLa (mmol·L^{-1})	8.2 ± 3.1	7.8 ± 3.1

* $P < 0.05$.

be higher compared with RP ($P = 0.10$) and compared with C ($P = 0.08$), but RPE for AMP–RP was similar to that for C (Fig. 2). BLa at 134 m·min^{-1} was higher ($P < 0.05$) for AMP–RP compared with C (Fig. 2) after similar resting values (1.1 ± 0.3). BLa was not measured for *P*.

Responses at TM speeds of 134 to 241 m·min^{-1}. During running across all speeds, $\dot{V}O_2$ was not significantly different between AMP–RP and C (Fig. 3A). There was also no significant difference in HR between AMP–RP and C (Fig. 3B). However, for five of the six matched pairs, HR for AMP–RP was higher than that for C at every speed (mean = +13%; ranging from +10 to 15%), and in the remaining pair, HR for AMP–RP was higher than that for matched C at all speeds >174 m·min^{-1}. Consequently, the absolute HR–$\dot{V}O_2$ relationship in AMP–RP is shifted to slightly higher HR (+12–15 beats·min^{-1}; Fig. 4). Although submaximal BLa tended to be higher in AMP–RP compared with C across speeds (134 to 241 m·min^{-1}), there were no significant differences.

Relative HR–relative oxygen uptake relationship. In the association between relative HR (%HR$_{max}$) and relative $\dot{V}O_2$ (%$\dot{V}O_{2max}$; Fig. 5), there was no difference between AMP–RP and C, respectively, in mean ± SD for intercept (36.5 ± 8.9 and 36.7 ± 9.1, respectively), slope (0.64 ± 0.01 and 0.64 ± 0.1, respectively), SEE (1.69 ± 0.8 and 1.16 ± 0.3, respectively), and Pearson's *r* correlation (0.97 ± 0.03 and 0.99 ± 0.01, respectively) of subjects' individual linear regressions. %HR$_{max}$ values calculated at 50%, 60%, 70%, and 80% $\dot{V}O_{2max}$ on the basis of individual linear regression equations for AMP and C were similar to %HR$_{max}$ values obtained using the ACSM formula, %HR$_{max}$ = 0.73(%$\dot{V}O_{2max}$) + 30 (Fig. 6). Furthermore, the ACSM formula-predicted %HR$_{max}$ was not significantly different from the actual %HR$_{max}$ for AMP–RP or C in any submaximal stage.

DISCUSSION

As hypothesized, the use of an RP for AMP resulted in a 15% lower energy cost of running and 10% lower HR compared with P during submaximal running. This is analogous to previous findings that energy return technology introduced in prosthetic feet results in a 5%–10% reduction in energy cost during TM walking (18,28) and 11% reduction during TM running at 120–147 m·min^{-1} (18). The energy cost at higher speeds could not be

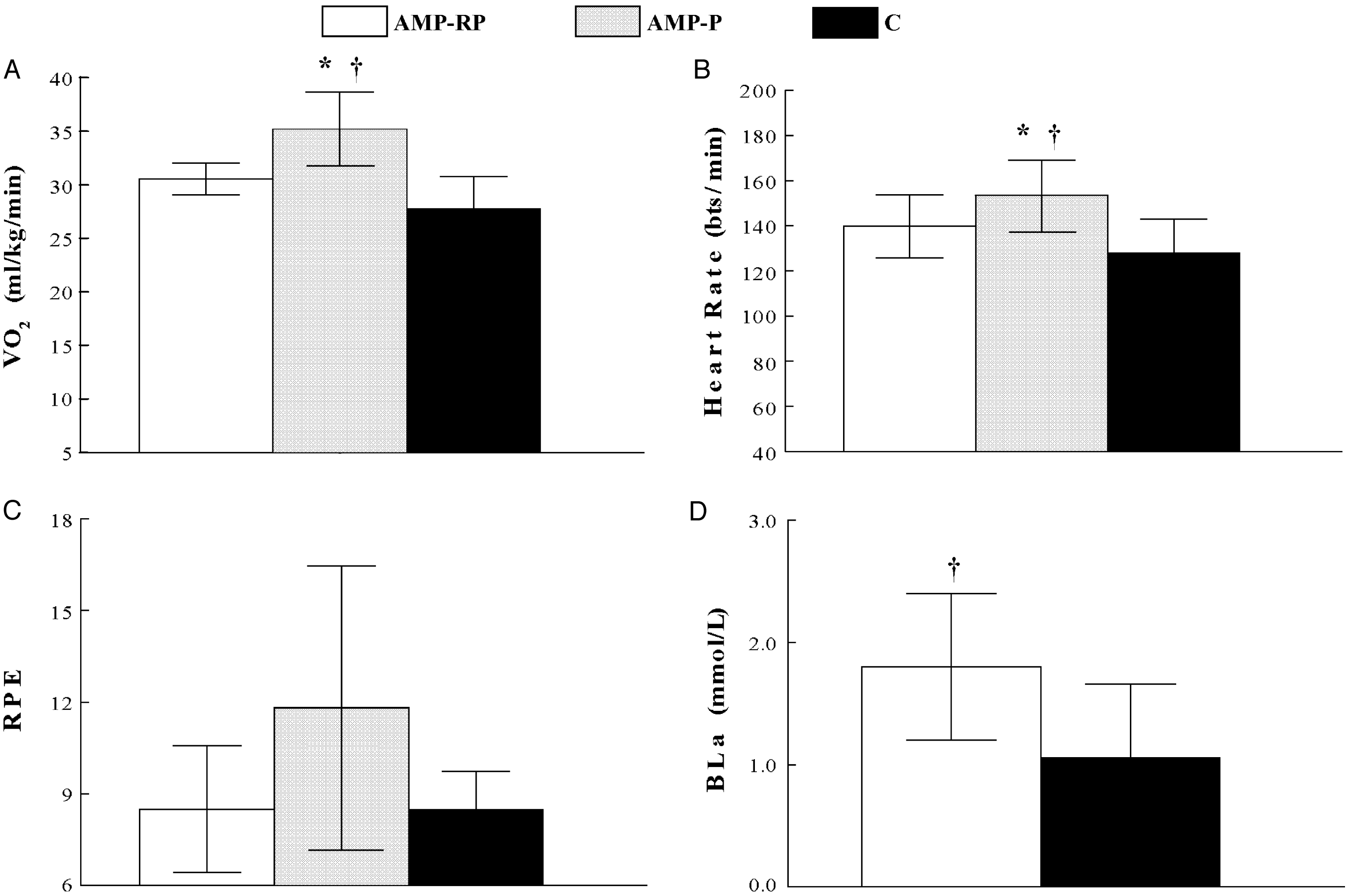

FIGURE 2—Steady state oxygen uptake ($\dot{V}O_2$) (A), heart rate (HR) (B), rating of perceived exertion (RPE) (C), and blood lactate (BLa; D) for amputees (AMP) under two different prosthesis conditions, traditional prosthesis (P) and running-specific prosthesis (RP), versus matched nonamputees (C) during treadmill (TM) running at 134 m·min^{-1}. *Significant difference from RP, $P < 0.05$. †Significant difference from C, $P < 0.05$.

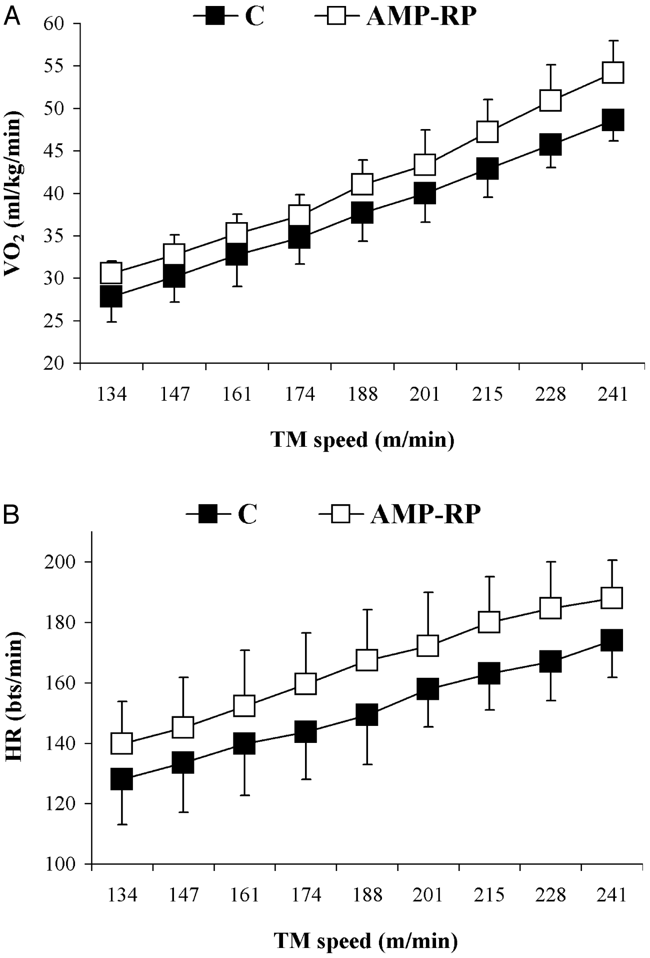

FIGURE 3—Oxygen uptake ($\dot{V}O_2$; A) and heart rate (HR; B) for amputees using running-specific prosthesis (AMP–RP) and matched nonamputees (C) during treadmill (TM) running of 134 to 241 m·min^{-1}.

compared between RP and P in the present study because of the inability of AMP subjects to run fast when using P. The dynamic response prosthetic feet included in the TM running comparisons by Hsu et al. (18) represented the newest energy return prosthetic technology at that time and are similar to the everyday walking prostheses used in the P trial in the present study. At a TM speed of 134 m·min^{-1}, the mean oxygen uptake for P (35.2 ± 3.5 mL·kg^{-1}·min^{-1}) agreed with that measured by Hsu et al. (18) for dynamic response feet (34.2–36.0 mL·kg^{-1}·min^{-1}). There was no comparable trial to RP in the study of Hsu et al.

Because the RP is specifically designed for improving running economy, it has been recently questioned if RP reduces energy cost to the extent of providing an unfair advantage to AMP over C (24,31). This has been of particular interest for a highly competitive bilateral AMP sprinter whose 400-m time was remarkably close to qualifying for the 2008 Olympic Games in Beijing. Although peak TM speed as measured in this study is not synonymous with peak running speed (i.e., maximal sprinting), before this investigation, there have been no comparative studies for AMP using RP technology compared with C during running at any speed. Although we observed that the energy cost of running in RP was similar to that in C, there was no evidence of a physiological advantage over C in cardiovascular strain or metabolic cost. The energy cost for AMP–RP was not lower than C while running at TM speeds 134–241 m·min^{-1} (i.e., averaging 8%–13% higher), and was similar to the 10%–15% higher energy cost recently reported for transtibial AMP (wearing dynamic prosthetic feet) compared with matched controls during *walking* at speeds ranging from 54 to 107 m·min^{-1} (12,20). Not surprising, the difference we report between AMP and C in energy cost is much less than that reported in studies using non–energy return prosthetic feet (16%–60%) (11,36) or testing subjects with bilateral transfemoral (49%) (15) and unilateral transfemoral (30%–60%) (12) limb loss. Even in the case of the one bilateral AMP in our study, the energy cost of running in RP was within ±2% of a matched C at every speed.

Another major finding of the present study is that RP permitted AMP to achieve similar peak TM speed and aerobic capacity to C but at a higher HR_{max}. There was also a tendency for higher HR in AMP compared with C at submaximal running speeds. One potential explanation for higher HR in AMP is the effect that the missing (amputated) muscle mass and thigh muscle atrophy of the residual limb may have on hemodynamics. Stroke volume response to exercise is highly dependent on the preload condition of the heart, most notably the effect of skeletal muscle pumps on venous return. Previous studies have demonstrated diminished stroke volume and cardiac output responses (6,22) and increased HR/$\dot{V}O_2$ ratio (16) during upper body ergometry exercise in spinal cord injured paraplegics compared with individuals without impairment. Changes in diastolic vessel diameter and flow were investigated in highly trained able-bodied and physically challenged athletes including AMP (21). Stroke volume (mL), volumetric blood flow (mL·min^{-1}), and lumen size

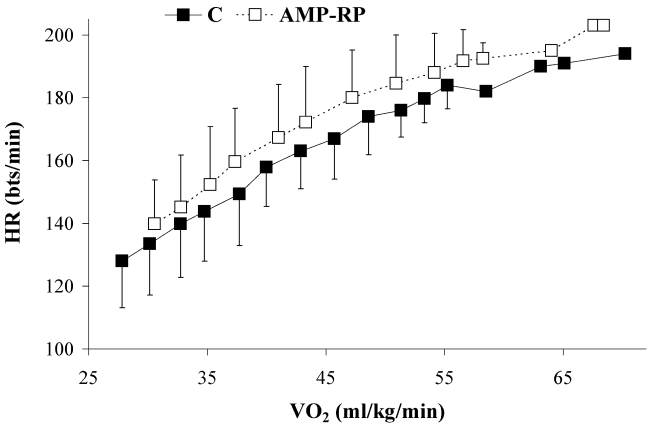

FIGURE 4—Heart rate (HR)–oxygen uptake ($\dot{V}O_2$) relationship in amputees using running-specific prosthesis (AMP–RP) versus matched nonamputees (C) during submaximal and maximal treadmill (TM) running.

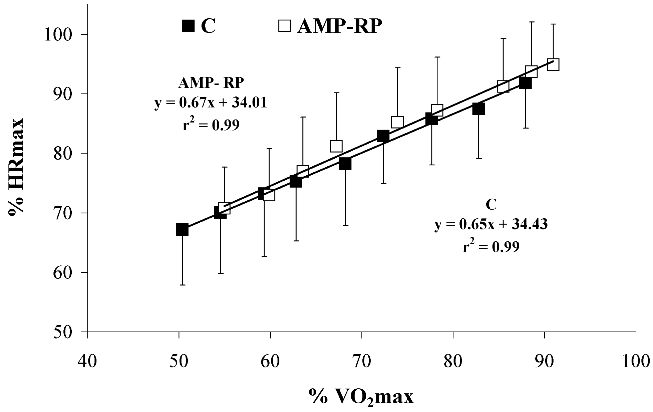

FIGURE 5—Relative HR–relative oxygen uptake relationship in amputees using running-specific prosthesis (AMP–RP) versus matched nonamputees (C) during treadmill (TM) running of 134 to 241 m·min^{-1}. The mean relative HR (%HR$_{\max}$)–relative oxygen uptake (%$\dot{V}O_{2\max}$) relationship in AMP–RP is similar in intercept and slope to C.

relative to body surface area (mm^2·m^{-2}) in the common femoral artery proximal to the amputated limb in AMP were lower than those in the intact side and also lower compared with able-bodied untrained athletes and trained athletes (21). Although open to debate (26,34), $\dot{V}O_{2\max}$ may be limited by maximal cardiac output from an inability to sustain stroke volume when tachycardia limits ventricular filling (13). If AMP have compromised venous return, then a higher HR$_{\max}$ for AMP in the present study might be explained by a greater ventricular filling challenge at maximal effort. Future studies should further examine the higher HR$_{\max}$ and the trend for higher submaximal HR in AMP as well, with a larger sample size.

Appropriate exercise prescriptions are needed for individuals with disability to meet the goals of optimizing physical function and health (8). Therefore, another objective of this study was to investigate the appropriate use of %HR$_{\max}$ to prescribe exercise intensity for AMP. It was hypothesized that HR relative to $\dot{V}O_2$ would be elevated in AMP regardless of prosthesis design. We observed that the absolute HR–$\dot{V}O_2$ relationship in AMP–RP was similar in slope despite a trend for higher HR compared with C. This difference was virtually eliminated when HR was expressed relative to the measured HR$_{\max}$ found in AMP. Furthermore, a published equation (1,25) was able to predict relative HR from relative exercise intensity for AMP and C equally in every exercise stage. Related literature examining the HR–$\dot{V}O_2$ relationship in paraplegics suggests that increased venous pooling from the absence of skeletal muscle pumps in the lower extremities elevates submaximal HR relative to $\dot{V}O_2$ (17,29,32). However, similar to our findings, the %HR–%$\dot{V}O_2$ relationship in sedentary paraplegics during arm crank ergometry (16) and in highly trained wheelchair athletes during wheelchair ergometry (14) is comparable to unimpaired controls. In contrast, a large dissociation (threefold greater) between change in %HR$_{\max}$ relative to change in %$\dot{V}O_{2\max}$ with added prosthetic mass was observed in transtibial AMP (23) during fast walking (107 m·min^{-1}). This is also in contrast to the present study where the magnitude of effect for use of P instead of RP on AMP HR (+10%) and AMP oxygen cost (+15%) was comparable. The discrepancy between studies might be explained, in part, because Lin-Chan et al. (23) used age-predicted rather than measured HR$_{\max}$, which we observed to be 7 beats·min^{-1} lower for AMP.

For exercise prescription in AMP, we conclude that it is appropriate for trained transtibial AMP using RP to calculate "target zones" on the basis of relative HR to establish run training intensity. It should be noted, however, that maximal HR should be measured instead of estimated on the basis of age because, as demonstrated in this group of transtibial AMP, age-predicted HR$_{\max}$ may underestimate true values, particularly compared with similarly aged C. Whether this discrepancy is unique to the subjects studied here merits further investigation.

The benefits of regular exercise are well known and are a current focus of public health initiatives for the general population as well as for the chronically ill and disabled. There is a greater incidence of cardiovascular disease in AMP, both from concomitant medical conditions common in this population, as well as the sedentary lifestyle adopted by many after amputation (5). While using P, our trained AMP displayed higher HR and perceived effort despite a modest running speed (134 m·min^{-1} or 7.46-min·km^{-1} pace) compared with RP. P clearly limits the ability for AMP to perform more vigorous activity, whereas the RP facilitates achievement of similar peak TM speed and relative aerobic capacity as athletes without limb loss. However, a transtibial RP can cost US $12–15,000 and requires replacement after approximately 700 km for an 80-kg runner. Currently, medical reimbursement is limited for prosthetic treatment and specialty prostheses making the cost–benefit ratio impractical for most AMP, except those

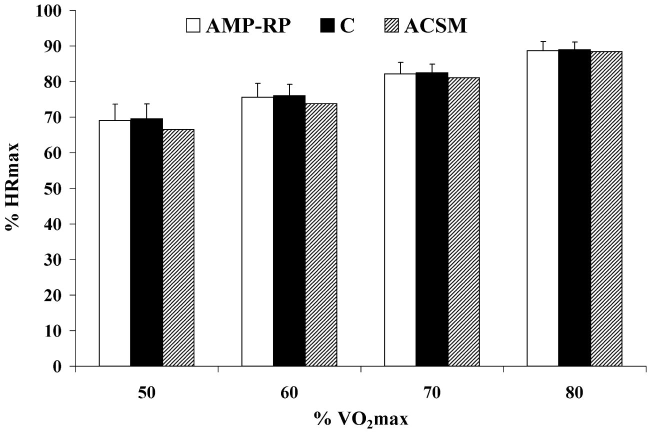

FIGURE 6—Actual and American College of Sports Medicine's (ACSM) regression equation-calculated relative HR (%HR$_{\max}$) at the indicated relative exercise intensities (%$\dot{V}O_{2\max}$) for amputee (AMP) and matched nonamputees (C).

who pursue competitive running or sports with the potential for corporate sponsorship. If the monetary costs of prostheses designed for running become more affordable in the future, more widespread accessibility would permit greater participation in vigorous activity for all AMP.

In summary, the use of RP with energy return technology significantly attenuates HR and energy cost during submaximal running compared with a traditional prosthesis for transtibial AMP. Furthermore, an RP permits trained AMP to attain peak TM speed and aerobic capacity comparable to similarly trained nonamputee runners despite a higher maximal HR. The energy cost of submaximal running for AMP using RP is also not significantly different from their nonamputee counterparts despite the tendency for higher submaximal HR. There is no evidence that RP provides AMP a physiological advantage over C via enhanced running economy or attenuated perceived effort and cardiovascular responses. Current prediction equations on the basis of the relative HR–$\dot{V}O_2$ relationship seem to be appropriate for prescribing exercise intensity for transtibial AMP using RP but may not equally apply with use of traditional prostheses.

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