

CLINICAL REPORT

Research Device to Preproduction Prototype: A Chronology

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Abstract—This paper describes the evolution of the Wheelchair Aerobic Fitness Trainer (WAFT), a wheelchair ergometer developed for determination of aerobic capacity and the diagnosis of coronary artery disease in lower limb disabled persons whose mobility depends primarily on the manual wheelchair. The device was originally developed for use in research studies to determine peak exercise capacity in persons with spinal cord injuries and other lower limb disabilities and to formulate associated graded exercise stress test protocols. In subsequent research, the device was incorporated into a specially designed testing station for the detection of coronary artery disease in persons who cannot adequately undergo treadmill or cycle ergometry testing because of lower limb disabilities. Based on the usefulness of the device for both rehabilitation and diagnostic purposes, the WAFT has been brought into the technology transfer process of the Department of Veterans Affairs Rehabilitation Research and Development Service. Under a contract with Packer Engineering, Inc., Naperville, IL, development of a preproduction version of the device and six units for field evaluation has commenced. The preproduction prototype of the WAFT has incorporated numerous improvements over the original device and promises to expand the potential for future research, rehabilitation, and diagnostic applications.

Key words: *aerobic fitness, cardiorespiratory health, coronary artery disease, mobility impairment, spinal cord injury, WAFT, wheelchair ergometer.*

INTRODUCTION

A major focus of our research has been the cardiorespiratory health of persons with lower limb disabilities. Access to a viable wheelchair ergometer that could be used to simulate the full range of exertional stress imposed by manual wheelchair propulsion was a necessity. From the very beginning, the decision was made that the form of exercise used in testing and conditioning must be physiologically, biomechanically, and psychologically specific to the primary mode of travel used by persons with lower limb disabilities. We also felt that the exercise test conditions for determination of aerobic capacity and the diagnosis of coronary artery disease for persons with lower limb disabilities should be equivalent to those currently offered to the nondisabled. This is especially important given that many wheelchair-dependent persons adopt a sedentary lifestyle. This fact was confirmed by data collected from 51 apparently healthy male spinal cord injured volunteers who participated in research conducted in our laboratory. Among these subjects only 10% reported engaging in any form of regular physical activity greater than that required for activities of daily living. Such lack of physical activity leads to significant decrements in physical fitness and an increased risk of cardiovascular disease.

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¹ Wheelchair Graded Exercise Test for Persons with Lower Limb Disabilities. Final Report on the Department of Veterans Affairs Rehabilitation R&D Project No. B398-RZ. W.E. Langbein and M.H. Hwang, 1991.

In response to the foregoing considerations, the Wheelchair Aerobic Fitness Trainer (WAFT) was designed and constructed at the Edward Hines, Jr. VA Hospital, Rehabilitation Research and Development Center (Rehab R&D) in Hines, IL. Specifications used in the design and construction of the first version of the device included patient safety, durability, appearance, ease of access and operation, and footprint similar to that of a commercial treadmill. In addition, the WAFT was intended to accommodate an individual's personal wheelchair, be accessible by the wheelchair user with minimal assistance, and provide flexibility in setting workloads so that the degree of cardiovascular stress could be readily controlled, thereby enabling the testing and conditioning of persons with lower limb disabilities who possess widely varied exercise capacities.

The WAFT evolved through several generations, incorporating improvements in both mechanical and electronic features and addressing such design challenges as roller configuration, method of creating progressive resistance, and mechanisms for wheelchair loading/unloading. The next section presents a brief description of the last version of the WAFT. It is this version that has been used in our laboratory over the past 5 years (see **Figure 1** and **Figure 2**); a more complete description appears elsewhere (1).

DEVICE DESCRIPTION

Wheelchair Aerobic Fitness Trainer: Development Phase One

The user/patient mounts the WAFT by backing his/her wheelchair up a pair of ramps which are tilted at an 8° angle during loading and unloading (**Figure 1**). The loading ramps are adjustable for different sizes of standard, lightweight, and sport wheelchairs. The wheelchair is backed up the ramps until the rear wheels rest on three rollers built into each ramp. The rollers were configured to accept a 61-cm-diameter wheel and provide an even distribution of the weight of chair and rider during wheeling. A lever on each ramp is pushed forward to level the ramps and form a stable platform. When the ramps are in the down position (**Figure 1**), the indentations used to position the front casters are closed and the forward-most roller is locked so it

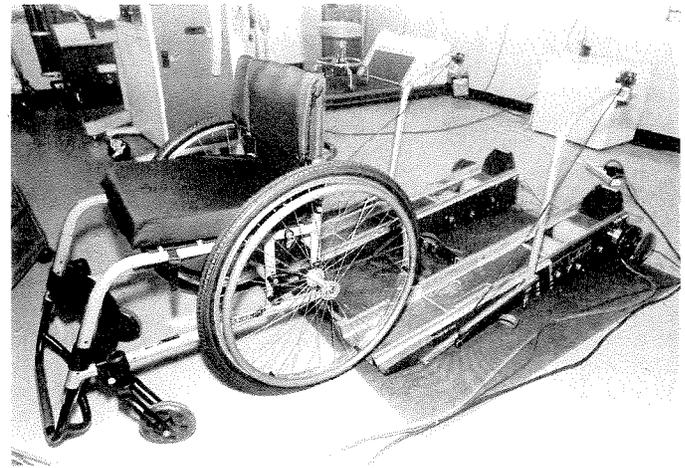


Figure 1. Wheelchair Aerobic Fitness Trainer—Phase One shown with the ramps down in preparation for loading the wheelchair.

cannot turn. In the level position (**Figure 2**), the rear wheelchair wheels turn freely on the rollers and the front wheels are secured in the open indentations.

Each rear wheel of the wheelchair is cradled and rotates on three weighted rollers, 16 cm long by 10 cm in diameter (**Figure 2**). Variable braking resistance is applied to each rear wheel via a magnetic eddy current braking assembly. To make the brakes effective at speeds commonly used in daily wheelchair propulsion, it was necessary to make modifications to the braking assemblies (1). Seven manually-selected resistance settings are available, and the braking units may be disengaged so that a wheelchair can be “free-wheeled” on the

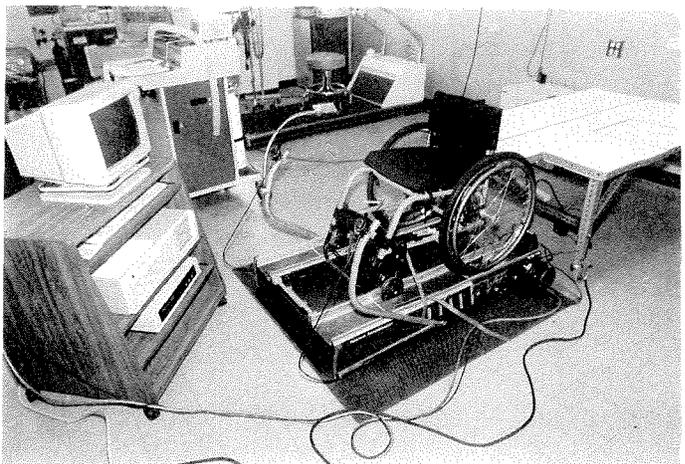


Figure 2. Wheelchair Aerobic Fitness Trainer—Phase One shown in position for exercise with computer and prototype echocardiography imaging table.

device. An inertial flywheel is factory-mounted on the axle of each braking assembly. Based on the qualitative judgments of a number of manual wheelchair users who tested the configuration, the inertial flywheel, weighted rollers, and magnetic eddy current brakes appear to produce conditions that simulate actual manual wheelchair propulsion. The resistance applied to each wheel may be manipulated independently to accommodate the objectives and physical abilities of the wheelchair user. Workloads are created by (a) increasing the resistance setting; (b) increasing speed at a given resistance setting; or (c) increasing both resistance setting and speed.

A 286 IBM-compatible computer is interfaced to the WAFT to monitor wheel speed from which it calculates power output, distance traveled, and projected wheelchair heading (Figure 2). The computer also times the duration of each exercise stage and provides storage of individual performance records. Elapsed time, speed of each wheel, and projected heading are displayed on the color monitor of the computer in both digital and graphic form as motivational feedback to the user/patient. Wheel speed for each wheel is also displayed on a pair of small analog panel meters.

A series of speed-torque calibration experiments enabled us to specify the relationships among wheel speed, resistance setting, and the power used over an interval of time (1). The power output relations were used to develop exercise test protocols to accommodate differing levels of cardiorespiratory fitness (see "Research/Clinical Application of Device," p. 439). These protocols and the WAFT are currently being used in an ongoing study to evaluate the clinical usefulness of a new technique for the detection of coronary artery disease (CAD) in persons who cannot adequately undergo treadmill or cycle ergometry testing because of lower limb disabilities. In this study, a specially designed imaging table is adjoined to the WAFT (Figure 2), and wheelchair ergometry graded exercise testing is combined with digital two-dimensional echocardiography.

Given the commercial viability of the device for both rehabilitation and diagnostic purposes, a Request for Evaluation was submitted to the Department of Veterans Affairs, Rehabilitation Research and Development Service, Technology Transfer Section (Baltimore, MD) to bring the WAFT into the Services's technology transfer process. Following

review by a panel of clinicians, the request was approved, contract performance specifications were developed, and a request for competitive proposals was announced in appropriate publications. After competitive proposals were received, Packer Engineering, Inc., Naperville, IL, was awarded a contract for development of a preproduction version of the device and six units for field evaluation. The knowledge gained regarding design and function during Phase One development of the WAFT served as the basis for the contract specifications for the preproduction prototypes. Packer's project engineers have made extensive modifications to the original design of the WAFT while meeting or exceeding the contract specifications.

Wheelchair Aerobic Fitness Trainer: Development Phase Two

The preproduction prototype WAFT utilizes a new dolly system designed to self-adjust to the wheelchair front caster width and to capture and immobilize the casters (see Figure 3). The wheelchair user backs his/her chair up and over a 10° plate until the front casters contact guide bars which move two parallel slotted plates into position so that the casters drop into the slots. Several sets of interchangeable plates are provided to fit various caster sizes. The casters are strapped to the plates with Velcro™ straps as an additional safety precaution and to keep the chair securely anchored during exercise. The caster plates are attached to tracks located on each side of the ergometer frame. As the wheelchair user backs up a 5.5° main ramp, the casters, secured in the plates, follow a straight-line course up the ramp until the chair is level and the rear wheels drop into indentations that house the ergometer rollers. A two-position momentary switch operates a linear actuator which locks the position of the dolly at each side of the ergometer. To ensure that wheel and roller meet at a 90° angle regardless of wheel diameter and camber, a second switch-activated linear actuator brings the rollers forward under the wheels. To unload the wheelchair, the steps in the loading sequence are reversed; the speed of descent must be controlled by the patient.

The preproduction prototype WAFT uses a pair of weighted aluminum rollers, 6.5 inches in diameter and 10.5 inches in length. Computer-controlled magnetic particle brakes are used to create a variable resistance. A 386, 33 MHz IBM-compatible com-

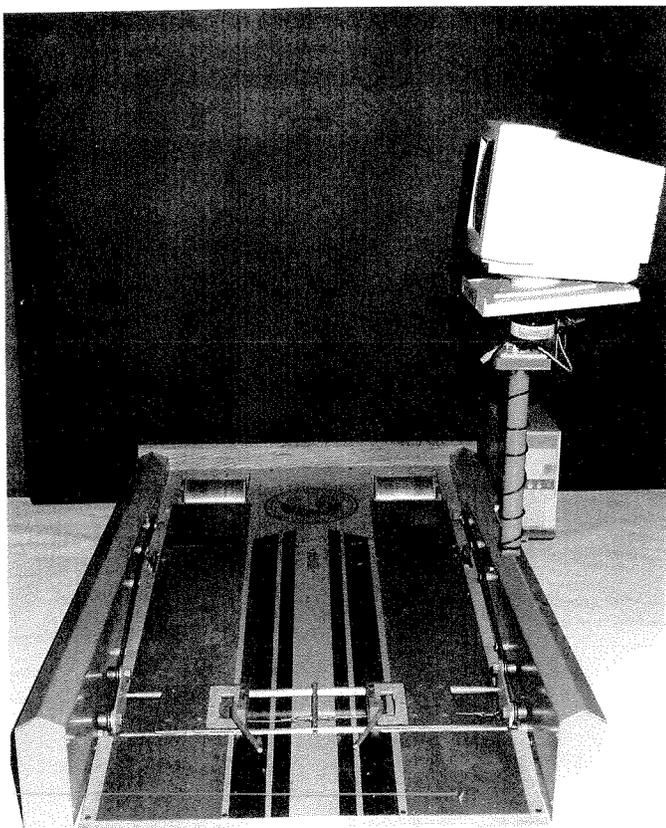


Figure 3. Wheelchair Aerobic Fitness Trainer—Phase Two shown from the front with caster dolly in loading position, rollers disengaged, computer monitor moved aside for loading.

puter (software by Computer Application Specialists, San Diego, CA) is interfaced to the WAFT. Based on the parameters of an operator-specified protocol, the computer controls the timing of each exercise stage and sends a controlling signal to the particle brakes to set the desired resistance at the beginning of each stage. The computer also samples speed and direction signals for each wheel. These signals are produced by digital encoders mounted on the axle of each roller.

The WAFT's computer and keyboard are mounted at the side of the ergometer for easy access by the clinician. The monitor is attached to a flexible arm to allow optimal positioning of the screen for the exercising patient (see **Figure 3** and **Figure 4**). The computer stores (by patient name and identification number) the test/conditioning protocol for each exercise session, including duration of exercise, target speed, and resistance level for each exercise stage. The clinician/technician may inter-

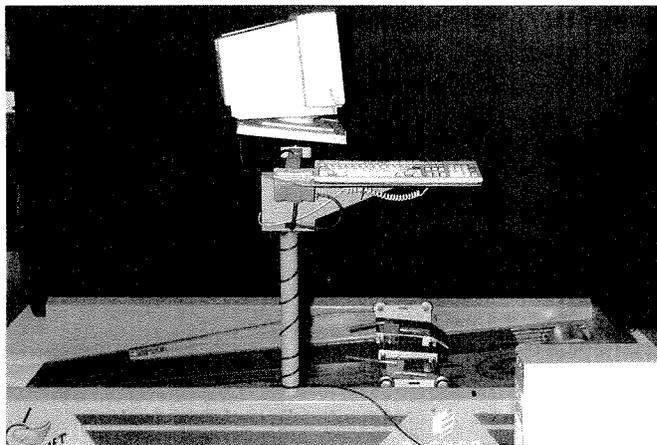


Figure 4. Wheelchair Aerobic Fitness Trainer—Phase Two shown from the side with caster dolly in locked position, computer monitor positioned for patient viewing; clinician access to keyboard and actuator control switches shown.

rupt an exercise session for any reason with a keystroke and may resume after a pause of any length without loss of information.

During exercise, the SVGA color monitor on the computer provides the wheelchair user with numeric and graphic feedback. The display shows current exercise stage and resistance setting, actual versus target speeds for each wheel, accumulated distance, actual versus target expenditure of kilocalories, elapsed time for the current stage, total elapsed time for the session, and an indication of projected wheelchair heading (see **Figure 5**). At the conclusion of exercise, an exercise performance report is stored under the patient's name and may be recalled for review or printing by the clinician at any time. The report includes duration, brake setting, average wheel speed, and power output for each exercise stage.

RESEARCH/CLINICAL APPLICATION OF DEVICE

Empirical evidence used to specify the operating characteristics of the WAFT was generated from a series of projects. In the first project, the results of successive calibration experiments were used to establish two wheelchair exercise test protocols. One protocol was intended for patients with lower limb disabilities and symptoms of coronary artery disease and/or apparently healthy persons with low initial

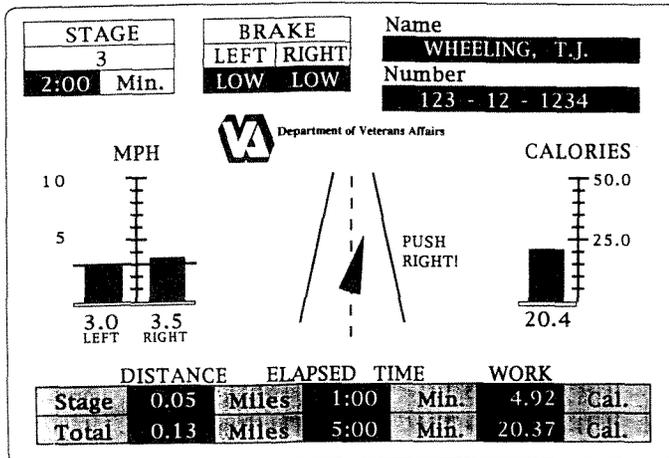


Figure 5.

Wheelchair Aerobic Fitness Trainer—Phase Two motivational feedback screen showing exercise stage duration and brake setting, actual and target speeds for each wheel, projected wheelchair heading, cumulative and target kilocalories, distance traveled and elapsed time for current stage, and total for session.

levels of physical fitness; a second for apparently healthy persons with average to above-average initial levels of physical fitness. Rate of incremental work loads distinguished the protocols.

Phase One Wheelchair Aerobic Fitness Trainer vs. Arm Crank Ergometry

The purpose of the second project was to (a) establish the validity of the WAFT for determining the peak exercise capacity of a heterogeneous sample of persons with spinal cord injuries and other lower limb disabilities; (b) compare the peak metabolic responses of persons with lower limb disabilities who completed stress test protocols using continuous arm crank ergometry (ACE) and continuous and intermittent wheelchair ergometry (WCE); and, (c) analyze the differentiated ratings of perceived exertion given by lower limb disabled subjects during different modes of upper body exercise. Fifty-one males, 17 to 69 years old—with quadriplegia, paraplegia, amputation(s), or lower limb fractures—were assigned to three experimental groups: upper-level injury (ULI), $C_5 - T_3$ ($n=12$); mid-level injury (MLI) $T_4 - T_{10}$ ($n=19$); and lower-level injury (LLI), below T_{10} or lower limb fractures ($n=20$). All subjects completed three maximal graded exercise test protocols, one intermittent and one contin-

uous on the Phase One WAFT, and one continuous on an arm crank ergometer.

Experimental group means for peak power output ($p<0.0001$) and tidal volume ($p<0.009$) were significantly greater during ACE than WCE, whereas peak measures of minute ventilation ($p<0.036$) and breathing frequency ($p<0.0001$) were significantly greater during WCE than ACE. There were no significant mean differences between continuous and intermittent WCE stress test protocols. Significant between-group differences were found for (a) peak measures of oxygen uptake; (b) minute ventilation; (c) tidal volume; (d) heart rate and rate pressure product for continuous WCE and ACE; and oxygen uptake, minute ventilation, tidal volume, breathing frequency, heart rate, and rate pressure product for the WCE intermittent protocol.

Correlation coefficients between peak measures of oxygen uptake, minute ventilation, and heart rate for WCE and ACE were 0.91, 0.85, and 0.95, respectively ($p<0.001$). In addition, 88 to 90 percent of the total variance between differentiated RPE for continuous WCE and ACE was accounted for in these analyses. This finding and the strength of the association observed between the criterion ACE exercise test and the experimental WCE was interpreted as empirical evidence that the Phase One WAFT and graded exercise stress test protocol provide a valid measure of both the physiological and psychophysiological factors that contribute to the peak functional capacity of persons with lower limb disabilities.

The measured increases in metabolic equivalents (METs) with increasing stages of the wheelchair stress test follow the general principles for exercise testing proposed by the American Heart Association and American College of Sports Medicine (2,3). Additionally, a substantial portion of this data has been used to set normative standards for aerobic fitness for persons with spinal cord injuries and other lower limb disabilities.¹

A third project focused on the hemodynamic responses of lower limb disabled subjects to WCE and ACE. **Table 1** presents age, peak rate pressure product (RPP), and peak heart rate values for 76 lower limb disabled patients tested in the authors'

¹Wheelchair Graded Exercise Test for Persons with Lower Limb Disabilities. Final Report on the Department of Veterans Affairs Rehab R&D Project No. B398-RZ. W.E. Langbein and M.H. Hwang, 1991.

Table 1.

Mean (\pm standard deviation) for age, rate pressure product (RPP) (RPP = heart rate \times systolic blood pressure), and peak heart rate during maximal wheelchair and arm crank exercise performed by apparently healthy persons with lower limb disabilities.

Parameter	Wheelchair Ergometry		Arm Crank Ergometry	
	Upper Level Injuries (n = 16)	Lower Level Injuries (n = 55) and Fractures (n = 5)	Upper Level Injuries (n = 15)	Lower Level Injuries (n = 42) and Fractures (n = 5)
Age	32 (\pm 11.0)	41 (\pm 10.9)	31 (\pm 10.7)	41 (\pm 10.9)
RPP	11912 (\pm 3308)	25281 (\pm 4690)	11383 (\pm 3071)	24851 (\pm 4166)
Heart Rate	120 (\pm 20)	166 (\pm 22)	118 (\pm 20)	167 (\pm 22)

Upper Level Injuries C₅-T₂; Lower Level Injuries T₃-L₅ and Fractures

laboratory.² Peak RPP were slightly greater for WCE exercise tests as compared to ACE exercise tests, indicating equal or greater potential for inducing myocardial ischemia. It should be noted that peak RPP is probably underestimated for both WCE and ACE because blood pressure was measured immediately upon cessation of exercise.

We are currently conducting pilot wheelchair exercise echocardiography (WC EX + ECHO) using a unique testing station developed at the Hines Rehab R&D Center (see **Figure 2**). Symptom-limited wheelchair graded exercise tests have been completed by 41 lower limb disabled patients with known or suspected CAD (**Table 2**). The mean RPP and heart rates shown in **Table 2** were derived from data on all patients who took the wheelchair exercise test. As a result, the variability was large. Under the condition, "exercise tests with angiography," patients were frequently stopped by the supervising cardiologist due to signs and/or symptoms well before reaching predicted maximal values. Additionally, data included patients who were, at the time of testing, taking medications that lowered blood pressure and/or heart rate during exertion (i.e., beta receptor antagonists and calcium channel blockers).

Within two months of the WCE exercise test, 14 patients underwent coronary angiography. Of these 14 individuals, two had angiography prior to WCE testing and were referred to our laboratory for evaluation of antianginal therapy. Thirteen of the 14 angiograms showed significant CAD with \geq 50

percent reduction in luminal diameter of at least one major epicardial coronary artery. Of these 14 cases, there were 10 true positive, one true negative, two nondiagnostic, and one false negative exercise tests. Thus, the overall diagnostic accuracy was 79 percent. The patient with a false negative test was being tested for evaluation of antianginal therapy. Review of the Hines VA Hospital patient records revealed no cardiac events in those patients (16 negative and 11 nondiagnostic) not completing angiographic assessments (follow-up 1 to 12 months). These preliminary results from our WCE exercise test compare favorably with the findings for lower body exercise as reviewed by DeTrano and Froelicher (4). Based on these observations, we have concluded that our system of exercise testing may offer a viable alternative to more costly pharmacologic stress testing procedures for diagnostic evaluation of selected patients with lower limb disabilities.

SUMMARY AND CONCLUSIONS

The Phase Two WAFT incorporates several improvements relative to its predecessor. The innovative caster capture system and self-centering rollers make the updated device accessible to almost any wheelchair except three-wheeled racing chairs; future generations will be adaptable for racing chairs. Given the relatively low incline of the loading ramp, our pilot tests revealed that, with the exception of some persons with quadriplegia, most subjects were able to mount and dismount the WAFT with a minimum of assistance. Subject safety is maximized

² Unpublished additional observations made as part of an extension of Rehab R&D Project No. B398-RZ, not included in Final Report.

Table 2.

Mean (\pm standard deviation) for age, peak rate pressure product (RPP = heart rate \times systolic blood pressure), peak heart rate, percentage of predicted maximal heart rate $[(220 - \text{age}) \div \text{peak heart rate}]$ during symptom limited wheelchair exercise (WCE) performed by persons with lower limb disabilities and suspected CAD.

Parameters	WCE Test and Angiography (n = 14)	WCE Test and Angiography with Nondiagnostic Tests Removed (n = 12)	WCE Test Without Angiography (n = 27)
Age (yr)	64 (\pm 6.6)	64 (\pm 6.8)	65 (\pm 8.0)
RPP	20920 (\pm 6726)	22398 (\pm 6033)	21132 (\pm 5520)
Peak Heart Rate	129 (\pm 27)	134 (\pm 26)	128 (\pm 24)
% Predicted HR _{max}	83 (\pm 16)	86 (\pm 16)	82 (\pm 14)

by the electronically interlocked system of switches (i.e., the rollers cannot be disengaged until the dolly assembly is in locked position). Though these switches must be operated by a clinician or technician, the exercise session itself, once initiated, is completely computer-controlled and no further intervention is required. Finally, the braking assembly used in the Phase One WAFT configuration offered 7 manually-selected resistance settings. While the software incorporated in the updated WAFT allows the clinician/technician a choice of only three resistance settings (low, medium, and high), these designations may be recalibrated at any time via the computer to produce any useful combination of increasing resistance levels (i.e., protocols employ a selection of discrete stages along a continuum of workloads). This feature allows the exercise protocols to be tailored to a wide variety of capabilities. It also has great future potential for research in the investigation of optimal test protocols and the evaluation of physiological responses as they relate to a workload ramp.

As progress on the Phase Two WAFT continues, the Phase One device remains in use. Increasing numbers of WAFT exercise tests have been requested by clinicians whose lower limb disabled patients present symptoms of coronary artery disease. Moreover, previously undocumented CAD was found in several apparently healthy individuals who volunteered for our research. Early intervention in these patients may have profound effects on long-

term quality of life and future medical expenses. In a relatively short time the WAFT, with exercise stress echocardiography, has had a significant impact on the health care provided to veterans.

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