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Metabolic Responses to Exercise

SIMPLIFIED METHOD AND PROGRAM FOR INCREMENTAL EXERCISE PROTOCOL DEVELOPMENT

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ABSTRACT

Robergs RA. Simplified method and program for incremental exercise protocol development. ***JEP****online* 2007;10(2):1-23. There is currently no simplified method to assist exercise physiologists in developing incremental protocols tailored to each individual. The purpose of this project was to develop a computer program to automatically and rapidly compute needed features of an incremental exercise protocol, such as the initial (stage 1) intensity, stage duration and intensity increments in order to attain VO_2max within a pre-determined and entered total protocol duration. Such a program was developed using LabVIEW (National Instruments, Austin TX), and based on data generated from the program, charts were developed to assist exercise physiologists in developing protocols with manual computation. The additional findings from the project were that treadmills need %grade increments as low as 0.1 % to support protocol development across a range of VO_2max values, linear VO_2 increment/stage rates, and short stage durations. In addition, to keep protocol durations between 8 and 12 min, endurance trained subjects should start a protocol at a moderate intensity, thereby allowing for VO_2 increments that remain below 5 mL/kg/min/min.

Key Words: VO_2max, Treadmill Walking, Running, Cycling

INTRODUCTION

The early development of treadmill exercise testing was based on defined protocols varying in belt speed (mi/hr) and %grade (Equation 1) for the treadmill, and cadence and external load for cycle ergometry.

$$\%grade = \left(\frac{rise}{run}\right) \times 100 = \left((\tan o) \times 100\right) \qquad \text{Equation 1}$$

Examples of such protocols for the treadmill were the Bruce (1), Balke (2), Naughton (3) and Costill and Fox (4) (Table 1), which were developed during the 1950's to 1970's, and tested for validity during and after this time period (4-13). Table 2 presents some common incremental protocols for cycle ergometry from Astrand (14,15) and McArdle et al. (12). However, as is clear from Tables 1 and 2, the steady state VO_2 estimates for the stages of these protocols reveal a clear time constraint for individuals of different endurance fitness. For example, a person with a VO_2max of 70 mL/kg/min would require >21 min to attain this value using the Bruce protocol, >59 min with the Balke, >71 min with the Naughton, and >11 min with the Costill protocol. For cycle ergometry, and assuming a body weight of 80 kg, the McArdle and Astrand protocols would require >46 and 15 min, respectively. Clearly, the development and use of subject-specific protocols is warranted in exercise physiology.

The importance of protocol duration has been emphasized in recent research, where Astorino et al. (16) had 26 young subjects (16 men and 10 women), aged 21 $\pm$ 3 yr, perform incremental treadmill VO_2max tests of approximately 6, 10, and 14 min durations. VO_2max was not different between the 6 min and 10 min duration, but was significantly lower in the 14 min duration, revealing that protocols shorter than typical (< 12 min) are superior for testing VO_2max. Recent research by Yoon et al. (17) also supports the need for short protocol durations for VO_2max measurement, with a duration of 8 min being optimal for highest VO_2max measurement. Yoon et al. also showed that this time issue was more important for well trained to elite endurance athletes than moderately trained to sedentary individuals.

The time constraints that exist for incremental exercise testing require the development of subject-specific, or individualized, protocols. For treadmill protocols, the variable nature of the VO_2 demand for increasing treadmill grade complicates this task. For example, a grade increment of 2% amounts to an increase in metabolic demand (VO_2) of 1.93 and 4.82 mL/kg/min at 4 and 10 mi/Hr, respectively. As such, the transition within a protocol from speed to %grade increments will require a %grade increment in VO_2 demand identical to the speed increment VO_2 demand of the protocol, and this %grade increment will vary depending on the final speed attained in the protocol. Depending on the fitness level of the subject, such maximal speeds could vary from 3.6 to 11 mi/hr.

Due to the variety of athletic and health states of individuals that can present themselves to an exercise physiology laboratory for either of research or professional testing, it would be convenient to use a nomogram, or computer program, that can easily compute the required increments in speed and %grade while constrained to a test duration between 8 to 10 min. While this need is arguably greater for treadmill running protocols, such a computational nomogram or program could also easily be developed for treadmill walking and cycle ergometry, based on the research validated metabolic equations for steady state VO_2 during walking (18), running (18) and cycle ergometry (19-21).

Table 1. Four commonly used protocols for treadmill exercise testing.

Bruce: Normal and high risk					
Stage	**Time#**	**Speed***	**%Grade**	**VO2^**	**Slope~**
1	3	1.7	10	16.71	5.57
2	3	2.5	12	24.14	2.47
3	3	3.4	14	33.21	3.02
4	3	4.2	16	42.22	3.01
5	3	5.0	18	52.01	3.26
				Mean Slope	***2.94***
Naughton: Cardiac and high risk					
Stage	**Time#**	**Speed***	**%Grade**	**VO2^**	**Slope~**
1	2	1	0	8.86	4.43
2	2	2	0	14.22	2.68
3	2	2	3.5	15.91	0.84
4	2	2	7	17.60	0.84
5	2	2	10.5	19.29	0.84
6	2	2	14	20.97	0.84
7	2	2	17.5	22.66	0.84
8	2	2	22	24.35	0.84
9	2	2	25.5	26.04	0.84
10	2	2	29	27.73	0.84
				Mean Slope	***0.84***
Balke: Normal risk					
Stage	**Time#**	**Speed***	**%Grade**	**VO2^**	**Slope~**
1	2	3.4	2	23.36	11.68
2	1	3.4	3	24.18	0.82
3	1	3.4	4	25.00	0.82
4	1	3.4	5	25.82	0.82
5	1	3.4	6	26.64	0.82
6	1	3.4	7	27.46	0.82
7	1	3.4	8	28.28	0.82
8	1	3.4	9	29.10	0.82
9	1	3.4	10	29.92	0.82
10	1	3.4	11	30.74	0.82
11	1	3.4	12	31.56	0.82
12	1	3.4	13	32.39	0.82
				Mean Slope	***0.82***
Costill: Highly trained					
Stage	**Time#**	**Speed***	**%Grade**	**VO2^**	**Slope~**
1	2	8.9	0	51.20	25.60
2	2	8.9	2	55.50	2.15
3	2	8.9	4	59.79	2.15
4	2	8.9	6	64.08	2.15
5	2	8.9	8	68.38	2.15
6	2	8.9	10	72.67	2.15
7	2	8.9	12	76.96	2.15
8	2	8.9	14	81.26	2.15
9	2	8.9	16	85.55	2.15
				Mean Slope	***2.15***

#min; *mi/hr; ^mL/kg/min; ~mL/kg/min/min from stage 2 on

Table 2. Commonly used protocols for cycle ergometer exercise testing.

McArdle: Normal risk				
Stage	**Time#**	**Watts**	**VO2^**	**Slope˜**
1	2	150	2.28	1.14
2	2	163	2.43	0.08
3	2	176	2.56	0.08
4	2	189	2.74	0.09
5	2	202	2.89	0.08
6	2	215	3.04	0.08
7	2	228	3.19	0.08
8	2	241	3.34	0.08
9	2	254	3.49	0.08
10	2	267	3.64	0.08
			Mean Slope	***0.08***
Astrand: Normal risk males				
Stage	**Time#**	**Watts**	**VO2^**	**Slope˜**
1	2	100	1.70	0.85
2	2	150	2.29	0.29
3	2	200	2.86	0.29
4	2	250	3.45	0.29
5	2	300	4.03	0.29
6	2	350	4.61	0.29
7	2	400	5.19	0.29
8	2	450	5.77	0.29
			Mean Slope	***0.29***
Ramps				
Watts/min	**Slope˜**	**mL/kg/min+**		
10	0.402	5.03		
15	0.464	5.79		
20	0.525	6.56		
25	0.586	7.32		
30	0.647	8.09		
35	0.708	8.85		

#min; ^L/min for 80 kg male; ˜L/min/min; Mean Slope is calculated starting at stage 2 for step protocols; +for 80 kg male

The purpose of this project was to devise a computer program to compute metabolic demand increments in protocol development for walking, running and cycle ergometry. Based on this program, select examples of protocol increments are provided for several known, or estimated, input variables, and summary tables and charts are provided to allow easy computation of specific increment values for treadmill speed and %grade, as well as Watts (cadence independent) or kilogram load for a given cadence (cadence dependent) for cycle ergometry. Finally, recommendations are given for protocol development where the VO_2 increment (L/min/min) is computed, and where this value remains within a subject (fitness) specific narrow range across the protocol.

METHODS

Equations to estimate steady state VO_2 were used to compute changes in steady state VO_2 demands for given treadmill and cycle ergometry conditions. The equations used for walking and running were obtained from ACSM (18) (Equations 2, 3), whereas the equations used for cycle ergometry were the gender specific equations from Latin (19-21) (Equations 4, 5).

$$WalkingVO_2\left(mL/kg/\min\right)=\left(\left(0.1\times volts\right)+\left(\left(\frac{\%grade}{100}\right)\times 1.8\times volts\right)\right)+3.5$$ Equation 2

$$RunningVO_2\,(mL/kg/\min) = \left((0.2 \times volts) + \left(\left(\frac{\%grade}{100} \right) \times 0.9 \times volts \right) \right) + 3.5 \qquad \text{Equation 3}$$

$$CyclingVO_2\,(L/\min) = \left(\frac{(11.624 \times Watts) + 260 + (3.5 \times kg)}{1000} \right) \quad males \qquad \text{Equation 4}$$

$$CyclingVO_2\,(L/\min) = \left(\frac{(9.7892 \times Watts) + 205 + (3.5 \times kg)}{1000} \right) \quad females \qquad \text{Equation 5}$$

To calculate the change in VO_2 for given changes in either speed, %grade or Watts, a custom program was written using LabVIEW (National Instruments, Austin,TX), incorporating equations 2 to 5. Increments of 0.1 units were used for treadmill speed and grade, and 5 Watt increments were used for Watts. For cadence dependent cycle ergometers, data were computed for the kilogram load required for a given Watts and VO_2 (mL/min) increment for 60, 65, 70, 75, 80, 85 and 90 rev/min, assuming a 6 m/crank revolution constant.

An additional computer program (LabVIEW, National Instruments, Austin,TX) was developed to assist in protocol development, as detailed in Table 3 for input and computed variables. The main requirement of the program was to compute the exercise intensity at the start of the protocol and the VO_2 increment required to reach an expected VO_2max for a pre-determined protocol duration.

Table 3. The input and indicator (results) icon labels of the program user interface (see Figure 1).

Walking	Running	Cycle Ergometry
Input Variables		
Test duration (min)		
Stage duration (min)		
Stage 1 duration (min)		
Expected VO_2max (mL/kg/min)		
Speed duration (min)		Start Watts
Start speed (mi/hr)		Gender
		Weight (lbs)
		Cadence (rev/min)*
		Distance/Crank (m)*
Computed (indicator) Variables		
Start speed (mi/hr)		Watts increment
Max speed (mi/hr)		Load increment (kg)
Speed increment (mi/hr/stage)		
%grade increment (%grade/stage)		
Stages (#)		

*For cadence dependent cycle ergometers

To summarize this program for the treadmill modes, the program used the input variables to compute the start (stage 1) VO_2 requirement, the VO_2 protocol requirement for an increase to an estimated VO_2max, the protocol time from stage 1 to VO_2max, the protocol VO_2/min requirement, the protocol VO_2/stage requirement, the speed only mi/hr/stage requirement, the maximal protocol speed based on the time for speed input control, the maximal speed VO_2, and the %grade increment/stage for a required VO_2/stage at maximal protocol speed. The process was easier for cadence independent cycle ergometry. Based on the protocol time and the start Watts, a linear VO_2/min and VO_2/stage constant was computed. This requirement was then used in equation 4 or 5, based on gender, to solve for the Watts/stage increment. For cadence dependent cycle ergometers, the final computed variable was the kg load for a specific cadence, which was calculate from the Watts/stage increment using Equation 6. All final increments were rounded to the nearest 0.1 unit (mi/hr and %grade) or integer (Watts).

$$kgLoad = \left(\frac{6.118 \times Watts}{6 \times Cadence} \right) \quad \text{Equation 6}$$

Figure 1 presents the user interface (LabVIEW front panel) of the computer program, showing the control and indicator icons as detailed in Table 3. The user repeats the application of the program by modifying selected input parameters until a realistic protocol is developed. Typically, when concerned with treadmill protocols, such user initiated multiple iterations of the program are needed to make the maximal treadmill speed suitable for the subject. The most crucial input variable is the estimated VO_2max. Errors in this entry cause the protocol to be either too short or too long for the subject.

To allow application of these computations without the LabVIEW program, charts were also developed and directions provided for step-by-step progress in computations to derive incremental protocols for treadmill walking and running, and cycle ergometry for cadence independent and dependent options.

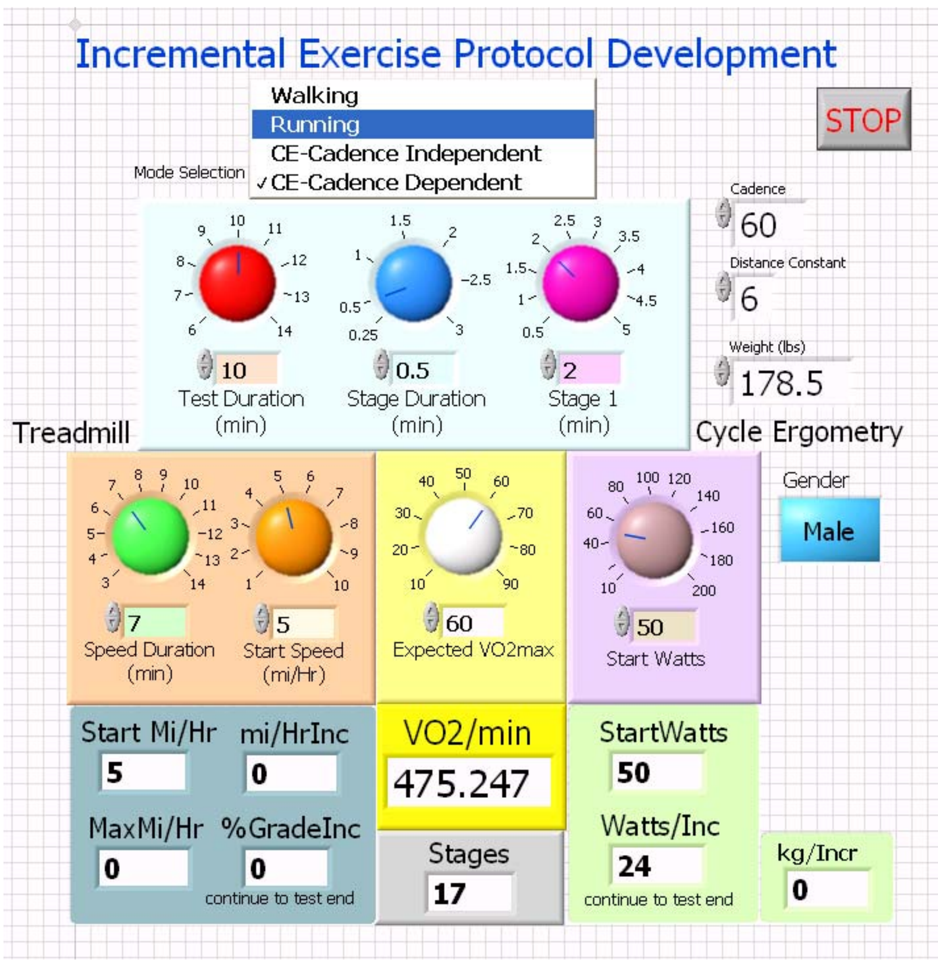

Figure 1. Front diagram (user interface) of the LabVIEW program written to automate protocol development for treadmill walking and running, and cycle ergometry. See text for explanation.

To assess the validity of the computations, sample conditions were also computed by hand calculator. In addition, examples of prior research exercise testing VO_2 data from treadmill running and cycle ergometry were used to compare VO_2 kinetic responses during exercise testing to steady state VO_2 data derived from equations 2 to 5. This graphic comparison was also required to assess the magnitude of the accumulating oxygen deficit throughout the protocol. As will be explained in the Results section, no correction factor was included in computations to account for the added exercise (protocol) time needed to reach VO_2max for non-steady state conditions.

RESULTS

Sub-sets of the VO_2 calculations are presented in Figure 2 for each exercise mode. Note the dilemma for developing treadmill protocols of the increasing VO_2 requirement for a given %grade as speed increases. The end speed of a protocol for a given athlete therefore determines the %grade VO_2 cost. To keep the VO_2 increment constant within a trial or between subjects when the peak treadmill speed changes, the %grade needs to be adjusted.

To demonstrate the results of the program, one example for each of walking, running and cycle ergometry is provided. This data is presented in Table 4. The walking protocol was for a mostly sedentary young individual, stating at 1.5 mi/hr for 2 min, followed by 0.4 mi/hr increments to 4.5 mi/hr. Thereafter, to maintain the same rate of increase in VO_2 demand (2.64 mL/kg/min/min), the protocol required increments of 0.6 %grade every 0.5 min to fatigue. The running protocol was for a well-trained endurance athlete, starting at 6.5 mi/hr for 2 min, followed by 0.5 mi/hr increments in speed every 0.5 min to 10.5 mi/hr. Thereafter, to maintain the same rate of increase in VO_2 demand (4.52 mL/kg/min/min), the protocol required increments of 0.9 %grade every 0.5 min to fatigue. The cycle ergometry protocol was for a moderately well trained athlete, starting at 150 Watts for 2 min, followed by 18 Watt increments every 0.5 min requiring 351.6 mL/min (4.4 mL/kg/min for 80 kg body mass) increase in VO_2 demand.

Table 4. Results of the program for example protocols for walking, running and cycle ergometry.

Variable	Walking	Running	Cycle Ergometry*
Input Variables			
estVO_2max	30	70	60
Test Duration	10	10	10
Stage Duration	0.5	0.5	0.5
Stage 1 Duration	2	2	2
Speed Duration	4.0	7	
Start Speed	1.5	6.5	
Start Watts			150
Computed (indicator) Variables			
Speed Increment	0.5	0.4	
Max Speed	3.5	10.5	
%Grade Increment	0.8	0.8	
Watts Increment			13
VO_2/min	2.81	3.96	310.3 [3.90]
Stages	17	17	17

*Male with body weight = 175 lb; VO_2max (mL/kg/min); Test, stage and speed durations (min); Speed (mi/hr); VO_2/min = mL/kg/min (walking, running) and mL/min [mL/kg/min] (cycling)

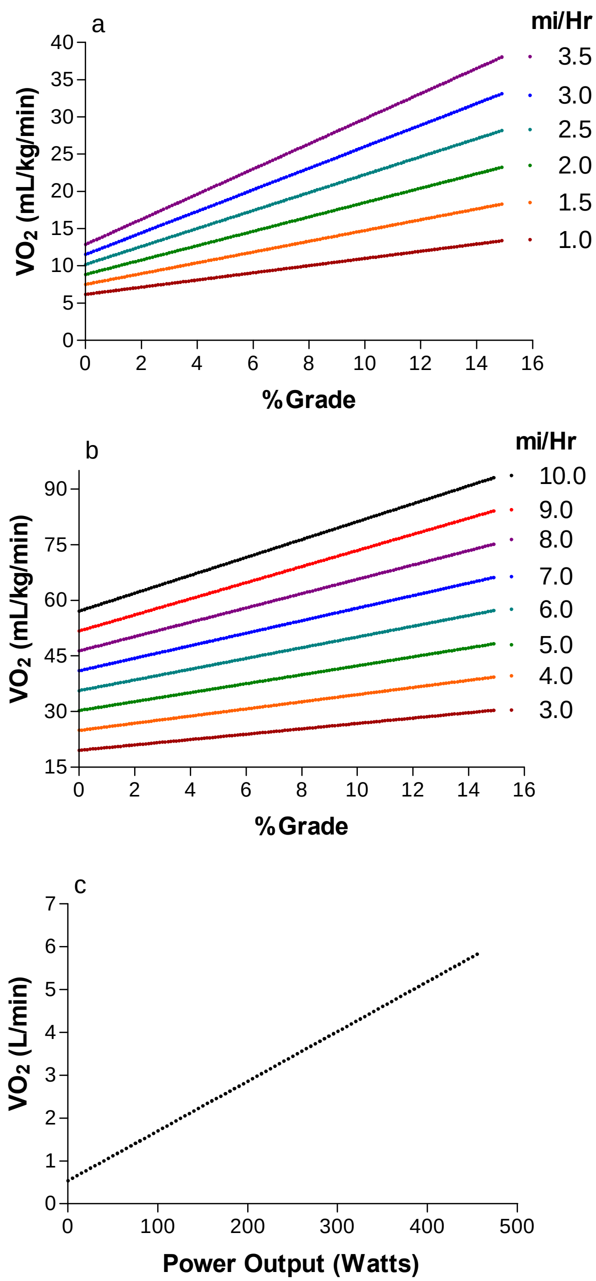

Figure 2. Computed data for steady state VO_2 with changes in treadmill speed and %grade for a) walking and b) running. c) VO_2 data are also presented for cycle ergometry using the equation for males and assuming a body mass of 175 lb (79.4 kg).

To assess the validity of this computational approach to developing incremental protocols, VO_2 data and incremental protocols from prior research were obtained and steady state VO_2 data were computed for the protocols. Data for a treadmilll running test, treadmill walking test, and cycle ergometry ramp test are presented in Figure 3 a, b and c.

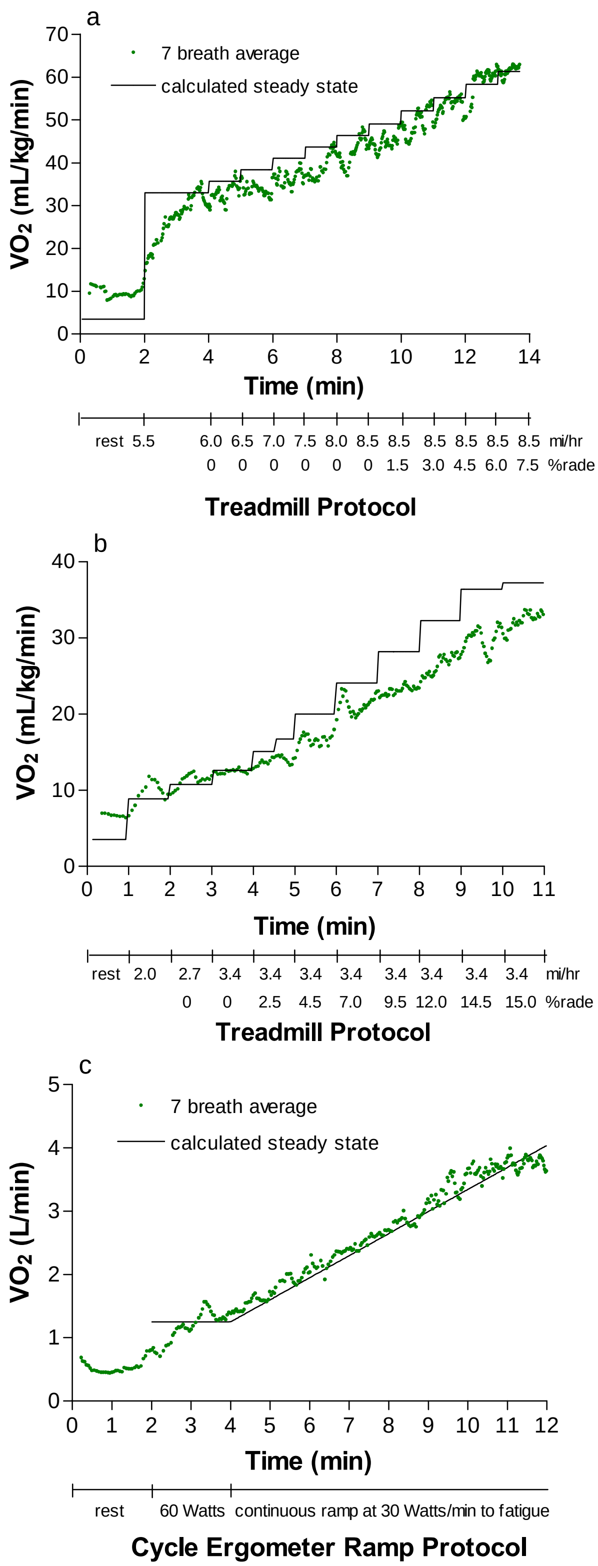

Figure 3. Measured VO_2 and computed steady state VO_2 for representative protocols and subjects during a) treadmill incremental exercise, b) treadmill walking incremental exercise, and c) cycle ergometry ramp incremental exercise.

Note the close responses between the computed steady stage VO_2 demand and actual measured VO_2 for the running and cycle ergometry ramp protocols. Furthermore, despite an increasing oxygen deficit during the last third of an incremental protocol, such a growing discrepancy is not seen in measured data due to added oxygen cost issues during intense exercise, such as the increased oxygen cost of ventilation. Such a variable VO_2 response during the latter stages of incremental exercise, make any oxygen deficit adjustment in the protocol development program and computational charts unnecessary. Nevertheless, the data from Figure 3b reveal a clear discrepancy between measured and estimated steady state VO_2. This treadmill walk protocol was not ideal in that the increments were not consistent across the protocol. The increasing oxygen deficit seen after minute 5 coincides with a large 1 min stage increase in %grade. This feature, in combination with the relatively large VO_2max of the subject for a walking protocol required a high VO_2 slope increment during the last 6 min of the protocol. This is a good example of the need for a consistent VO_2 demand increment across the protocol, as provided by the program and related chart data and related sequential computations as detailed next.

Charts 1 through 4 present tabulated data derived from the LabVIEW protocol development program. Chart 1 presents the VO_2 data for treadmill walking. Data are presented for 0.2 mi/hr increments in speed to 3.6 mi/hr, as well as for %grade increments from 0 to 15 %. The delta data (Δ) refer to the increment in VO_2 for a unit change in either speed or %grade. For example, the VO_2 cost for increasing 1 mi/hr while walking is 2.68 mL/kg/min. This cost increases with increases in %grade, as shown. The VO_2 cost for increasing 1 %grade is speed specific, varying from 0.1 to 1.74 mL/kg/min for 0.2 and 3.6 mi/hr, respectively. Completing the sequential calculations of Chart 2, requiring use of the data from Chart 1, will result in the development of an incremental protocol for treadmill walking.

Chart 3 presents the VO_2 data for treadmill running. Data are presented for 0.5 mi/hr increments in speed from 3.0 to 11.0 mi/hr, as well as for %grade increments from 0 to 15 %. The delta data (Δ) refer to the increment in VO_2 for a unit change in either speed or %grade. For example, the VO_2 cost for increasing 1 mi/hr while running is 5.36 mL/kg/min. As for walking, this cost increases with increases in %grade, and the VO_2 cost for increasing 1 %grade is speed specific, varying from 0.72 to 2.65 mL/kg/min for 3.0 and 11.0 mi/hr, respectively. Chart 4 provides the sequential calculations for the development of an incremental protocol for treadmill running.

Chart 5 presents the VO_2 data for cadence dependent cycle ergometry. Gender specific data are presented for 5 Watt increments in power output. Due to the needed addition of body weight adjusted resting VO_2, the VO_2 data presented need to have this resting VO_2 added to represent the true steady state VO_2 for a given Watts. Chart 6 provides the sequential calculations for the development of a cadence independent cycle ergometry incremental protocol. Chart 7 provides the sequential calculations for the development of a cadence dependent cycle ergometry incremental protocol.

Finally, Table 5 provides ΔVO_2 data for males and females for 2 Watt increments ranging from 4 to 40 Watts. The kg load values for each of 60, 65, 70, 75, 80, 85 and 90 rev/min are also provided, revealing the load increment required to increase anywhere from 4 to 40 Watts (assumes a 6 m distance/crank revolution constant).

Sample calculations for Charts 2, 4, 6, and 7 are provided in the Appendix.

Chart 1: Treadmill Walk Speed (mi/hr) and Grade (%Grade) VO_2 (mL/kg/min) Data

	%Grade																
mi/hr	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Δ/%G**
0	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	***0.00***
0.2	4.04	4.13	4.23	4.33	4.42	4.52	4.62	4.71	4.81	4.90	5.00	5.10	5.19	5.29	5.39	5.48	***0.10***
0.4	4.57	4.77	4.96	5.15	5.34	5.54	5.73	5.92	6.12	6.31	6.50	6.70	6.89	7.08	7.27	7.47	***0.19***
0.6	5.11	5.40	5.69	5.98	6.27	6.56	6.85	7.13	7.42	7.71	8.00	8.29	8.58	8.87	9.16	9.45	***0.29***
0.8	5.64	6.03	6.42	6.80	7.19	7.57	7.96	8.35	8.73	9.12	9.50	9.89	10.28	10.66	11.05	11.43	***0.39***
1.0	6.18	6.66	7.15	7.63	8.11	8.59	9.07	9.56	10.04	10.52	11.00	11.49	11.97	12.45	12.93	13.42	***0.48***
1.2	6.72	7.30	7.87	8.45	9.03	9.61	10.19	10.77	11.35	11.93	12.51	13.08	13.66	14.24	14.82	15.40	***0.58***
1.4	7.25	7.93	8.60	9.28	9.95	10.63	11.30	11.98	12.66	13.33	14.01	14.68	15.36	16.03	16.71	17.38	***0.68***
1.6	7.79	8.56	9.33	10.10	10.88	11.65	12.42	13.19	13.96	14.74	15.51	16.28	17.05	17.82	18.59	19.37	***0.77***
1.8	8.32	9.19	10.06	10.93	11.80	12.67	13.53	14.40	15.27	16.14	17.01	17.88	18.74	19.61	20.48	21.35	***0.87***
2.0	8.86	9.83	10.79	11.75	12.72	13.68	14.65	15.61	16.58	17.54	18.51	19.47	20.44	21.40	22.37	23.33	***0.97***
2.2	9.40	10.46	11.52	12.58	13.64	14.70	15.76	16.83	17.89	18.95	20.01	21.07	22.13	23.19	24.25	25.32	***1.06***
2.4	9.93	11.09	12.25	13.41	14.56	15.72	16.88	18.04	19.19	20.35	21.51	22.67	23.83	24.98	26.14	27.30	***1.16***
2.6	10.47	11.72	12.98	14.23	15.49	16.74	17.99	19.25	20.50	21.76	23.01	24.27	25.52	26.77	28.03	29.28	***1.26***
2.8	11.00	12.36	13.71	15.06	16.41	17.76	19.11	20.46	21.81	23.16	24.51	25.86	27.21	28.56	29.91	31.27	***1.35***
3.0	11.54	12.99	14.43	15.88	17.33	18.78	20.22	21.67	23.12	24.57	26.01	27.46	28.91	30.35	31.80	33.25	***1.45***
3.2	12.08	13.62	15.16	16.71	18.25	19.79	21.34	22.88	24.43	25.97	27.51	29.06	30.60	32.14	33.69	35.23	***1.54***
3.4	12.61	14.25	15.89	17.53	19.17	20.81	22.45	24.09	25.73	27.37	29.01	30.65	32.29	33.93	35.57	37.21	***1.64***
3.6	13.15	14.89	16.62	18.36	20.10	21.83	23.57	25.30	27.04	28.78	30.51	32.25	33.99	35.72	37.46	39.20	***1.74***
Δ	***2.68***	***3.16***	***3.64***	***4.13***	***4.61***	***5.09***	***5.57***	***6.06***	***6.54***	***7.02***	***7.50***	***7.99***	***8.47***	***8.95***	***9.43***	***9.92***	

Chart 2: Computations For Treadmill Walking Protocol Development

What is the subject's estimated VO_2max (mL/kg/min)? ………. *a*

What is your START speed? ………. *b*

What is your start speed VO_2? ………. *c*

(*get this from the walking speed %grade VO_2 Table*)

Calculate the protocol ΔVO_2 = *(a – c)* = ... *d*

How long will be your protocol duration (min)? ……… *e*

How long is stage 1 (min)? ………. *f*

Calculate the duration of your protocol after stage 1 = (*e* – *f*) = ………. *g*

Calculate the protocol ΔVO_2/min = (*d* / *g*) = ... *h*

How long will be all other stages (min)? ………. *i*

Calculate the protocol ΔVO_2/stage = (*h* * *i*) = ... *j*

Calculate the mi/hr/increment at 0 %grade = (*j / (26.8 * 0.1)*) = …… Round this to the nearest 0.1 unit = …….. *k*

Determine your max speed by using x number of *k* increments above *c* ………. *l*

(*Note, the maximal valid walking speed is 3.6 mi/hr*)

What is the ΔVO_2/%grade value for *l*? ………. *m*

(*get this from the walking speed %grade VO_2 Table*)

Calculate the %grade increment for *j* = (*j* / *m*) = ………. Round this to the nearest 0.1 unit = …….. *n*

Protocol = Start at ***b*** mi/hr for ***f*** min. ↑ speed ***k*** mi/hr every ***i*** min to ***l*** mi/hr, then ↑ %grade ***n***% every ***i*** min to fatigue.

Chart 3: Treadmill Run Speed (mi/hr) and Grade (%Grade) VO_2 (mL/kg/min) Data

	%Grade																
mi/hr	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Δ**
3.0	19.58	20.30	21.03	21.75	22.47	23.20	23.92	24.65	25.37	26.09	26.82	27.54	28.26	28.99	29.71	30.43	***0.72***
3.5	22.26	23.10	23.95	24.79	25.64	26.48	27.33	28.17	29.01	29.86	30.70	31.55	32.39	33.24	34.08	34.92	***0.84***
4.0	24.94	25.91	26.87	27.83	28.80	29.76	30.73	31.69	32.66	33.62	34.59	35.55	36.52	37.48	38.45	39.41	***0.96***
4.5	27.62	28.71	29.79	30.88	31.96	33.05	34.13	35.22	36.30	37.39	38.47	39.56	40.65	41.73	42.82	43.90	***1.09***
5.0	30.30	31.51	32.71	33.92	35.12	36.33	37.54	38.74	39.95	41.15	42.36	43.57	44.77	45.98	47.18	48.39	***1.21***
5.5	32.98	34.31	35.63	36.96	38.29	39.61	40.94	42.27	43.59	44.92	46.25	47.57	48.90	50.23	51.55	52.88	***1.33***
6.0	35.66	37.11	38.55	40.00	41.45	42.90	44.34	45.79	47.24	48.69	50.13	51.58	53.03	54.47	55.92	57.37	***1.45***
6.5	38.34	39.91	41.48	43.04	44.61	46.18	47.75	49.32	50.88	52.45	54.02	55.59	57.15	58.72	60.29	61.86	***1.57***
7.0	41.02	42.71	44.40	46.09	47.77	49.46	51.15	52.84	54.53	56.22	57.90	59.59	61.28	62.97	64.66	66.35	***1.69***
7.5	43.70	45.51	47.32	49.13	50.94	52.75	54.55	56.36	58.17	59.98	61.79	63.60	65.41	67.22	69.03	70.84	***1.81***
8.0	46.38	48.31	50.24	52.17	54.10	56.03	57.96	59.89	61.82	63.75	65.68	67.61	69.54	71.47	73.39	75.32	***1.93***
8.5	49.06	51.11	53.16	55.21	57.26	59.31	61.36	63.41	65.46	67.51	69.56	71.61	73.66	75.71	77.76	79.81	***2.05***
9.0	51.74	53.91	56.08	58.25	60.42	62.59	64.77	66.94	69.11	71.28	73.45	75.62	77.79	79.96	82.13	84.30	***2.17***
9.5	54.42	56.71	59.00	61.29	63.59	65.88	68.17	70.46	72.75	75.04	77.33	79.63	81.92	84.21	86.50	88.79	***2.29***
10.0	57.10	59.51	61.92	64.34	66.75	69.16	71.57	73.98	76.40	78.81	81.22	83.63	86.04	88.46	90.87	93.28	***2.41***
10.5	59.78	62.31	64.85	67.38	69.91	72.44	74.98	77.51	80.04	82.57	85.11	87.64	90.17	92.70	95.24	97.77	***2.53***
11.0	62.46	65.11	67.77	70.42	73.07	75.73	78.38	81.03	83.69	86.34	88.99	91.65	94.30	96.95	99.61	102.26	***2.65***
Δ	***5.36***	***5.60***	***5.84***	***6.08***	***6.32***	***6.57***	***6.81***	***7.05***	***7.29***	***7.53***	***7.77***	***8.01***	***8.25***	***8.50***	***8.74***	***8.98***	

Chart 4: Computations For Treadmill Running Protocol Development

What is the subject's estimated VO_2max (mL/kg/min)? ………. *a*

What is your START speed? ………. *b*

What is your start speed VO_2? ………. *c*

(*get this from the running speed %grade VO_2 Table*)

Calculate the protocol $\Delta VO_2 = (a - c)$ = ... *d*

How long will be your protocol duration (min)? ……… *e*

How long is stage 1 (min)? ………. *f*

Calculate the duration of your protocol after stage 1 = $(e - f)$ = ………. *g*

Calculate the protocol ΔVO_2/min = (d / g) = ... *h*

How long will be all other stages (min)? ………. *i*

Calculate the protocol ΔVO_2/stage = $(h * i)$ = ... *j*

Calculate the mi/hr/increment at 0 %grade = $(j / (26.8 * 0.2))$ = …… Round this to the nearest 0.1 unit = …….. *k*

Determine your max speed by using x number of *k* increments above *c* ………. *l*

(*Note, be sure that your subject can run comfortably at this speed*)

What is the ΔVO_2/%grade value for *l*? ………. *m*

(*get this from the running speed %grade VO_2 Table*)

Calculate the %grade increment for $j = (j / m)$ = ………. Round this to the nearest 0.1 unit = …….. *n*

Protocol = Start at ***b*** mi/hr for ***f*** min. ↑ speed ***k*** mi/hr every ***i*** min to ***l*** mi/hr, then ↑ %grade ***n***% every ***i*** min to fatigue.

Chart 5: Cycle Ergometry Watts-VO_2 (L/min) Data*

Watts	M	F	Watts	M	F	Watts	M	F	Watts	M	F	Watts	M	F
5	0.318	0.254	105	1.481	1.233	205	2.643	2.212	305	3.805	3.191	405	4.968	4.169
10	0.376	0.303	110	1.539	1.282	210	2.701	2.261	310	3.864	3.240	410	5.026	4.218
15	0.434	0.352	115	1.597	1.331	215	2.759	2.310	315	3.922	3.288	415	5.084	4.267
20	0.492	0.401	120	1.655	1.380	220	2.817	2.359	320	3.980	3.337	420	5.142	4.316
25	0.551	0.45	125	1.713	1.429	225	2.875	2.407	325	4.038	3.386	425	5.200	4.365
30	0.609	0.499	130	1.771	1.478	230	2.934	2.456	330	4.096	3.435	430	5.258	4.414
35	0.667	0.548	135	1.829	1.526	235	2.992	2.505	335	4.154	3.484	435	5.317	4.463
40	0.725	0.597	140	1.887	1.575	240	3.050	2.554	340	4.212	3.533	440	5.375	4.512
45	0.783	0.645	145	1.946	1.624	245	3.108	2.603	345	4.270	3.582	445	5.433	4.561
50	0.841	0.694	150	2.004	1.673	250	3.166	2.652	350	4.328	3.631	450	5.491	4.610
55	0.899	0.743	155	2.062	1.722	255	3.224	2.701	355	4.387	3.680	455	5.549	4.659
60	0.957	0.792	160	2.120	1.771	260	3.282	2.750	360	4.445	3.729	460	5.607	4.708
65	1.016	0.841	165	2.178	1.820	265	3.340	2.799	365	4.503	3.778	465	5.665	4.757
70	1.074	0.89	170	2.236	1.869	270	3.399	2.848	370	4.561	3.827	470	5.723	4.806
75	1.132	0.939	175	2.294	1.918	275	3.457	2.897	375	4.619	3.876	475	5.781	4.855
80	1.19	0.988	180	2.352	1.967	280	3.515	2.946	380	4.677	3.925	480	5.840	4.904
85	1.248	1.037	185	2.410	2.016	285	3.573	2.995	385	4.735	3.974	485	5.898	4.953
90	1.306	1.086	190	2.469	2.065	290	3.631	3.044	390	4.793	4.023	490	5.956	5.002
95	1.364	1.135	195	2.527	2.114	295	3.689	3.093	395	4.852	4.072	495	6.014	5.050
100	1.422	1.184	200	2.585	2.163	300	3.747	3.142	400	4.910	4.121	500	6.072	5.099

*** Data does not include resting VO_2 component. Rest VO_2 (L/min) = ((3.5 mL/kg/min x body mass (kg)) / 1000)**

Chart 6: Computations For Cycle Ergometry Cadence Independent Protocol Development

What is the subject's estimated VO_2max (mL/kg/min)? ………. *a*

What is the subject's body mass (kg)? ………. *b*

Calculate the subject's resting VO_2 = (3.5 * b) = ………. *c*

Remove the subject's resting VO_2 from VO_2max and express as mL/min = ((*a* * *b*) – *c*) = ………. *d*

What is your START Watts? ………. *e*

What is your start Watts VO_2 (mL/min)? ………. * 1000 = ………. *f*

(*get this from the cycle ergometry Watts-VO_2 (L/min) Table*)

Calculate the protocol ΔVO_2 = *(d – f)* = ... *g*

How long will be your protocol duration (min)? ……… *h*

How long is stage 1 (min)? ………. *i*

Calculate the duration of your protocol after stage 1 = (*h* – *i*) = ………. *j*

Calculate the protocol ΔVO_2/min = (*g* / *j*) = ... *k*

How long will be all other stages (min)? ………. *l*

Calculate the protocol ΔVO_2/stage = (k * *l*) = ... *m*

Calculate the Watts/increment = (*m / (6.118 * x)*) = ……. Round this to the nearest Watts = …….. *n*

(*Note, x=1.9 for males and 1.6 for females*)

Protocol = Start at ***e*** for ***i*** min. ↑ ***n*** Watts every ***l*** min to fatigue.

Chart 7: Computations For Cycle Ergometry Cadence Dependent Protocol Development

What is the subject's estimated VO_2max (mL/kg/min)? ………. *a*

What is the subject's body mass (kg)? ………. *b*

Calculate the subject's resting VO_2 = (3.5 * b) = ………. *c*

Remove the subject's resting VO_2 from VO_2max and express as mL/min = ((*a* * *b*) – *c*) = ………. *d*

What is your START Watts? ………. *e*

What is your start Watts VO_2 (mL/min)? ………. (L/min) * 1000 = ………. *f*

(*get this from the cycle ergometry Watts-VO_2 (L/min) Table*)

Calculate the protocol ΔVO_2 = *(d – f)* = ... *g*

How long will be your protocol duration (min)? ……… *h*

How long is stage 1 (min)? ………. *i*

Calculate the duration of your protocol after stage 1 = (*h* – *i*) = ………. *j*

Calculate the protocol ΔVO_2/min = (*g / j*) = ... *k*

How long will be all other stages (min)? ………. *l*

Calculate the protocol ΔVO_2/stage = (k * *l*) = ... *m*

What is the cadence? ………. *n*

Calculate the kg/increment for the cadence = (*m / (x* n * 6)*) = …… Round to a suitable increment = …….. *o*

(*Note, x=1.9 for males and 1.6 for females*)

Calculate the start kg load for *e* at *n* rev/min = ((*e* * 6.118) / (6 * *n*)) = …… Round to a suitable increment = …... *p*

Protocol = Start at ***e*** (***p*** kg load) for ***i*** min at ***n*** rev/min. ↑ ***o*** kg every ***l*** min to fatigue.

Chart 8: Cycle Ergometry Watts Increment-VO_2 (mL/min) and kg Load Data

			Kg Loads						
	Male	Female	Cadence Dependent (rev/min)						
Watts Incr	ΔVO_2	ΔVO_2	60	65	70	75	80	85	90
4	46	39	0.07	0.06	0.06	0.05	0.05	0.05	0.05
6	70	59	0.10	0.09	0.09	0.08	0.08	0.07	0.07
8	93	78	0.14	0.13	0.12	0.11	0.10	0.10	0.09
10	116	98	0.17	0.16	0.15	0.14	0.13	0.12	0.11
12	139	117	0.20	0.19	0.17	0.16	0.15	0.14	0.14
14	163	137	0.24	0.22	0.20	0.19	0.18	0.17	0.16
16	186	157	0.27	0.25	0.23	0.22	0.20	0.19	0.18
18	209	176	0.31	0.28	0.26	0.24	0.23	0.22	0.20
20	232	196	0.34	0.31	0.29	0.27	0.25	0.24	0.23
22	256	215	0.37	0.35	0.32	0.30	0.28	0.26	0.25
24	279	235	0.41	0.38	0.35	0.33	0.31	0.29	0.27
26	302	255	0.44	0.41	0.38	0.35	0.33	0.31	0.29
28	325	274	0.48	0.44	0.41	0.38	0.36	0.34	0.32
30	349	294	0.51	0.47	0.44	0.41	0.38	0.36	0.34
32	372	313	0.54	0.50	0.47	0.44	0.41	0.38	0.36
34	395	333	0.58	0.53	0.50	0.46	0.43	0.41	0.39
36	418	352	0.61	0.56	0.52	0.49	0.46	0.43	0.41
38	442	372	0.65	0.60	0.55	0.52	0.48	0.46	0.43
40	465	392	0.68	0.63	0.58	0.54	0.51	0.48	0.45

Note, body mass is not included in the ΔVO_2 data.

DISCUSSION

The manuscript and project is highly original, revealing for the first time computations in exercise physiology that allow for rapid and valid protocol development with linear increments in VO_2 demand for user-defined variables such as protocol length and stage durations. While this is relatively easy to accomplish for cycle ergometry, and has been routine in many commercial cadence independent cycle ergometers, no application of this sort has been applied to treadmill exercise.

Exercise physiologists who conduct treadmill exercise tests with clients of varied fitness and health status know the need for and difficulties in developing individualized protocols. The tables and charts of this manuscript provide the means to rapidly compute such protocols while retaining a constant VO_2 demand throughout the protocol.

Users should understand the importance of the VO_2max estimation. Errors in this estimation will influence the length of the actual exercise protocol. Protocol durations should remain between 8 and 12 min (16,17,22). Based on experience and recent research findings in exercise testing at this laboratory (17), endurance trained individuals should perform protocols with a duration closer to 8 than 12 min. Based on these facts, it is recommended that 10 min be used for the anticipated protocol duration, and underestimation of the expected VO_2max should be avoided. Underestimating VO_2max will lengthen the protocol time to fatigue, risking a lower than true VO_2max.

A potential limitation to these computations is that most commercial treadmills do not increment both speed and grade in 0.1 unit increments. Exercise physiologists should therefore be encouraged to purchase equipment with increments as low as 0.1 units for each of speed and %grade so that improved protocol development can be accomplished. In the Exercise Physiology Laboratories (EPL) at this university, there are several treadmills from different manufacturers and models, and these are presented in Table 5.

Table 5. The treadmills in the EPL.

Treadmill	***Speed Range (mi/hr)***	***Speed Increment (mi/hr)***	***%grade Range***	***%grade Increment***
Precor C966	0.5 - 16	0.1	-3.0 - 15	0.5
GE Marquet	0.1 - 13.5	0.1	0 - 25	0.1
Precor 966i	0.5 - 16	0.1	-3.0 - 15	0.5
Quinton Q Stress TM55	0.8 – 9.6	0.2	0 - 25	0.5

It is difficult to get a treadmill that incorporates a small enough %grade increment. The only treadmill in our laboratory that has an adequately small %grade increment is made by General Electric (GE). However, this treadmill is designed for walking protocols, and would not be suitable for an endurance-trained athlete requiring a running protocol. The Precor and Quinton treadmills are limited for use in their large %grade increment (0.5 %grade), and we have to design protocols that require increments divisible by 0.5. Treadmill manufacturers need to make their treadmills controlled to %grade increments of 0.1 %.

Finally, though it is not yet customary to develop incremental protocols that start at a moderate intensity, it is recommended that such a practice be employed where possible. This is especially important for highly trained individuals. For example, an athlete with a VO_2max of 72 mL/kg/min should not start a 10 min protocol at a low treadmill speed, such as 4 mi/hr, as this would require a large protocol ΔVO_2 of 47.06 mL/kg/min. Assuming a VO_2 demand from 4 mi/hr was attained within 2 min into the protocol, the remaining 8 min would require a ΔVO_2 of 5.9 mL/kg/min/min. While there is no research on changing rates of VO_2 increment for a constant protocol duration, at this time it is logical to remain conservative and view such larger VO_2 increments to be less conducive to accurate VO_2max measurement. Based on more than 20 years of exercise testing experience, it is presently wise to aim for protocol ΔVO_2 increments < 5 mL/kg/min/min. However, there is an urgent need for research on this topic to be performed and published.

APPENDIX

The following examples are base don the test conditions presented in Table 4.

Chart 2 Example: Treadmill Walking

\What is the subject's estimated VO_2max (mL/kg/min)? **30** *a*
What is your START speed? **1.5** *b*
What is your start speed VO_2? **7.52** *c*
(get this from the walking speed %grade VO_2 Table)
Calculate the protocol $\Delta VO_2 = (a - c)$ = **22.48** *d*
How long will be your protocol duration (min)? 10 *e*
How long is stage 1 (min)? **2** *f*
Calculate the duration of your protocol after stage 1 = (*e* – *f*) = **8** *g*
Calculate the protocol ΔVO_2/min = (*d* / *g*) = **2.81** *h*
How long will be all other stages (min)? **0.5** *i*
Calculate the protocol ΔVO_2/stage = (*h* * *i*) = **1.4** *j*
Calculate the mi/hr/increment at 0 %grade = (*j / (26.8 * 0.1)*) = 0.52
Round this to the nearest 0.1 unit = **0.5** *k*
Determine your max speed by using x number of *k* increments above *c* **3.5** *l*
(Note, the maximal valid walking speed is 3.6 mi/hr)
What is the ΔVO_2/%grade value for *l*? **1.69** *m*
(get this from the walking speed %grade VO_2 Table)
Calculate the %grade increment for *j* = (*j* / *m*) = 0.83
Round this to the nearest 0.1 unit = **0.8** *n*

Protocol = Start at ***1.5*** mi/hr for ***2*** min. ↑ speed ***0.5*** mi/hr every ***0.5*** min to ***3.5*** mi/hr, then ↑ %grade ***0.8***% every ***0.5*** min to fatigue.

Chart 4 Example: Treadmill Running

What is the subject's estimated VO_2max (mL/kg/min)? **70** *a*
What is your START speed? **6.5** *b*
What is your start speed VO_2? **38.34** *c*
(get this from the running speed %grade VO_2 Table)
Calculate the protocol $\Delta VO_2 = (a - c)$ = **31.66** *d*
How long will be your protocol duration (min)? **10** *e*
How long is stage 1 (min)? **2** *f*
Calculate the duration of your protocol after stage 1 = (*e* – *f*) = **8** *g*
Calculate the protocol ΔVO_2/min = (*d* / *g*) = **3.96** *h*
How long will be all other stages (min)? **0.5** *i*
Calculate the protocol ΔVO_2/stage = (*h* * *i*) = **1.98** *j*
Calculate the mi/hr/increment at 0 %grade = (*j / (26.8 * 0.2)*) = 0.37
Round this to the nearest 0.1 unit = **0.4** *k*
Determine your max speed by using x number of *k* increments above *c* **10.5** *l*
(Note, be sure that your subject can run comfortably at this speed)
What is the ΔVO_2/%grade value for *l*? **2.53** *m*
(get this from the running speed %grade VO_2 Table)
Calculate the %grade increment for *j* = (*j* / *m*) = 0.78
Round this to the nearest 0.1 unit = **0.8** *n*

Protocol = Start at ***6.5*** mi/hr for ***2*** min. ↑ speed ***0.4*** mi/hr every ***0.5*** min to ***10.5*** mi/hr, then ↑ %grade ***0.8***% every ***0.5*** min to fatigue.

Chart 6 Example: Cadence Independent Cycle Ergometry

What is the subject's estimated VO_2max (mL/kg/min)? **60** *a*
What is the subject's body mass (kg)? **79.4** *b*
Calculate the subject's resting VO_2 = (3.5 * b) = **277.9** *c*
Remove the subject's resting VO_2 from VO_2max and express as mL/min = ((*a* * *b*) – *c*) = **4486** *d*
What is your START Watts? **150** *e*
What is your start Watts VO_2 (mL/min)? 2.004 (L/min) * 1000 = **2004** *f*
(get this from the cycle ergometry Watts-VO_2 (L/min) Table)
Calculate the protocol ΔVO_2 = *(d – f)* = **2482** *g*
How long will be your protocol duration (min)? **10** *h*
How long is stage 1 (min)? **2** *i*
Calculate the duration of your protocol after stage 1 = (*h* – *i*) = **8** *j*
Calculate the protocol ΔVO_2/min = (*g / j*) = **310.25** *k*
How long will be all other stages (min)? **0.5** *l*
Calculate the protocol ΔVO_2/stage = (k * *l*) = **155.13** *m*
Calculate the Watts/increment = (*m / (6.118 * x)*) = 13.34
Round this to the nearest Watts = **13** *n*
(Note, x=1.9 for males and 1.6 for females)

Protocol = Start at ***150*** for ***2*** min. ↑ ***13*** Watts every ***0.5*** min to fatigue.

Chart 7 Example: Cadence Dependent Cycle Ergometry

What is the subject's estimated VO_2max (mL/kg/min)? 60 *a*
What is the subject's body mass (kg)? 79.4 *b*
Calculate the subject's resting VO_2 = (3.5 * b) = 277.9 *c*
Remove the subject's resting VO_2 from VO_2max and express as mL/min = ((*a* * *b*) – *c*) = 4486 *d*
What is your START Watts? 150 *e*
What is your start Watts VO_2 (mL/min)? 2.004 * 1000 = 2004 *f*
(get this from the cycle ergometry Watts-VO_2 (L/min) Table)
Calculate the protocol ΔVO_2 = *(d – f)* = 2482 *g*
How long will be your protocol duration (min)? 10 *h*
How long is stage 1 (min)? 2 *i*
Calculate the duration of your protocol after stage 1 = (*h* – *i*) = 8 *j*
Calculate the protocol ΔVO_2/min = (*g / j*) = 310.25 *k*
How long will be all other stages (min)? 0.5 *l*
Calculate the protocol ΔVO_2/stage = (k * *l*) = 155.13 *m*
What is the cadence? 75 *n*
Calculate the kg/increment for the cadence = (*m / (x* n * 6)*) = 0.184
Round to a suitable increment = 0.2 *o*
(Note, x=1.9 for males and 1.6 for females)
Calculate the start kg load for *e* at *n* rev/min = ((*e* * 6.118) / (6 * *n*)) = 2.04
Round to a suitable increment = 2.0 *p*

Protocol = Start at ***150*** Watts (**2** kg load) for ***2*** min at ***75*** rev/min. ↑ ***0.2*** kg every ***0.5*** min to fatigue.

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