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Equipment Testing and Validation

MAXIMAL EXERCISE TESTING USING THE ELLIPTICAL CROSS-TRAINER AND TREADMILL

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ABSTRACT

MAXIMAL EXERCISE TESTING USING THE ELLIPTICAL CROSS-TRAINER AND TREADMILL. **Lance C. Dalleck, Len Kravitz, Robert A. Robergs**. **JEP**online 2004;7(3):94-101. The purpose of this study was to compare the physiological responses during incremental exercise to fatigue using the elliptical cross-trainer and treadmill running. Twenty recreationally active individuals (10 men and 10 women, mean age, height, weight, and body composition = 29.5±7.1 yr, 173.3±12.6 cm, 72.3±7.9 kg, and 17.3±5.0 BF%) completed two randomized VO_2max tests: treadmill and Precor elliptical cross-trainer separated by 1-3 days. Breath-by-breath data were collected using a fast response turbine flow transducer and custom developed software with AEI oxygen and carbon dioxide electronic gas analyzers. All breath-by-breath data were smoothed using a 7-breath moving average. Criteria for attainment of VO_2max included two of the following: respiratory exchange ratio (RER) > 1.1, maximal heart rate (HR) within 15 b/min of the calculated value, or VO_2 plateau (ΔVO_2 < 50 mL/min with an increase in power output). Paired t-tests were performed to determine mean differences between VO_2max, maximal HR, maximal RER, and protocol duration. No significant differences ($p>0.05$) were found in VO_2max (47.9 vs. 47.3 ml/kg/min), maximal HR (186 vs. 184 b/min), maximal RER (1.22 vs. 1.25), and protocol duration (11.56 vs. 12.17 min) between elliptical crosstraining and treadmill running. In conclusion, this study revealed that the elliptical cross-trainer produced similar maximal physiological values compared to treadmill running during VO_2max testing.

Key Words: Maximal oxygen consumption (VO_2max), Maximal heart rate (MHR), Exercise mode

INTRODUCTION

Maximal oxygen uptake (VO_2max) is a fundamental measurement for the exercise physiologist (1). VO_2max refers to the highest rate at which oxygen can be taken up and consumed by the body during intense exercise (2). Traditionally, the magnitude of an individual's VO_2max has been viewed as a measure of aerobic fitness and overall health. Studies have consistently demonstrated an inverse relationship between VO_2max values and risk of all-cause mortality (3-4). Additionally, VO_2max has been considered an attribute required for success in endurance-related events. A classic study conducted at Ball State University in the 1960's confirmed the importance of VO_2max to endurance performance, with findings demonstrating a strong correlation between VO_2max values and 10-mile run times (5).

VO_2max may be determined using numerous exercise modes that activate large groups of muscle mass, provided the intensity of effort and protocol duration are sufficient to maximize aerobic energy transfer (6). Although treadmill exercise and cycle ergometry are the most common modes utilized for VO_2max testing, other types of exercise modes, including bench stepping, free, tethered, and flume swimming, swim-bench ergometry (7-8), in-line skating (9), NordicTrack cross-country skiing (10), roller-skating (11), simulated arm-leg climbing (12), arm crank and wheelchair exercises (13-15), and rowing ergometry, have also been employed to achieve VO_2max. Regardless of exercise mode, variations in VO_2max typically reflect the quantity of muscle mass activated during exercise (10,16). Treadmill exercise generally elicits the highest VO_2max values for the same untrained and/or recreationally trained individual performing different exercise mode VO_2max tests, although subject training specificity will also influence the magnitude of VO_2max values attained among different exercise modes (6). Elite-trained cyclists have been found to have similar treadmill and cycle ergometry VO_2max values. Likewise, untrained and trained collegiate swimmers achieve VO_2max values during swimming versus treadmill VO_2max tests of 80% and 90%, respectively, while elite swimmers attain similar or greater VO_2max values (17-19).

The elliptical cross-trainer has become increasingly popular in recent years as an alternative exercise mode in fitness centers and cardiac rehabilitation facilities. The elliptical cross-trainer is low-impact in nature and may be a more favorable exercise mode in different populations. It has been proposed to be beneficial to populations that are obese or restricted by back, knee, or other lower-body joint limitations (20). Research on this mode of exercise is lacking, with only one published study existing that investigates the physiological responses of elliptical cross-trainer exercise. Results from this investigation suggest there are similar submaximal physiological responses to elliptical cross-trainer exercise compared to treadmill exercise at equivalent rating of perceived exertion (RPE) levels (20). Presently, there is no research pertaining to VO_2max and the elliptical cross-trainer. The purpose of this study was to first develop gender-specific VO_2max protocols for different fitness levels and then to compare VO_2max values between the treadmill and elliptical cross-trainer.

METHODS

Subjects

Twenty recreationally active, healthy subjects (10 men, 10 women; ages 20 to 48 years) were recruited from the faculty, undergraduate, and graduate student populations at the university, as well as the surrounding community. The mean age, height, weight, and body composition are reported in Table 1. All subjects signed a written informed consent before volunteering for the study, and the university Human Subjects Institutional Review Board approved all procedures.

Table 1. Subject Characteristics (n=20)

Parameter	*Measurement*
Age (years)	29.5 ± 7.1
Height (cm)	173.3 ± 12.6
Weight (kg)	72.3 ± 7.9
Body Composition (%)	17.3 ± 5.0

Pre-testing procedures

Subjects were instructed to avoid eating food four hours prior to testing and to refrain from strenuous exercise 12 hours prior to testing. Testing sessions were separated by at least 24 hours to minimize subject fatigue. Subjects were weighed to the nearest 0.1 kg on a medical grade scale (Seca Corporation, Model #707, Columbia , MD) and

measured for height to the nearest 0.5 cm using a stadiometer (Ross Laboratories, Accustat Ross Stadiometer, Bardonia, NY).

Experimental procedures

Subjects were accustomed to treadmill exercise or walking and all had at least one familiarization session on the elliptical cross-trainer prior to testing. Prior to any testing session subjects were given detailed instruction on the exercise testing protocol. The exercise testing consisted of two randomized, maximal exercise trials (treadmill running and elliptical cross-trainer) designed to last approximately 8-12 min in duration each (21).

Treadmill protocol

On the treadmill, a modified Balke protocol was performed with subjects selecting a comfortable running speed that could be maintained for the duration of the test. After measuring resting expired gases for 2 min, subjects were gradually brought to the selected running speed for the first minute of the test, which was then maintained throughout the duration of the test. The first 3 min of the protocol were performed at 0% grade, thereafter, the treadmill grade was increased by 1%/min until volitional fatigue (Figure 1).

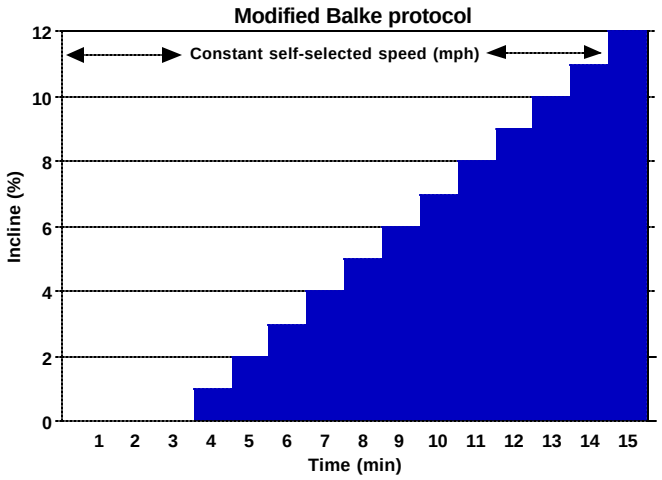
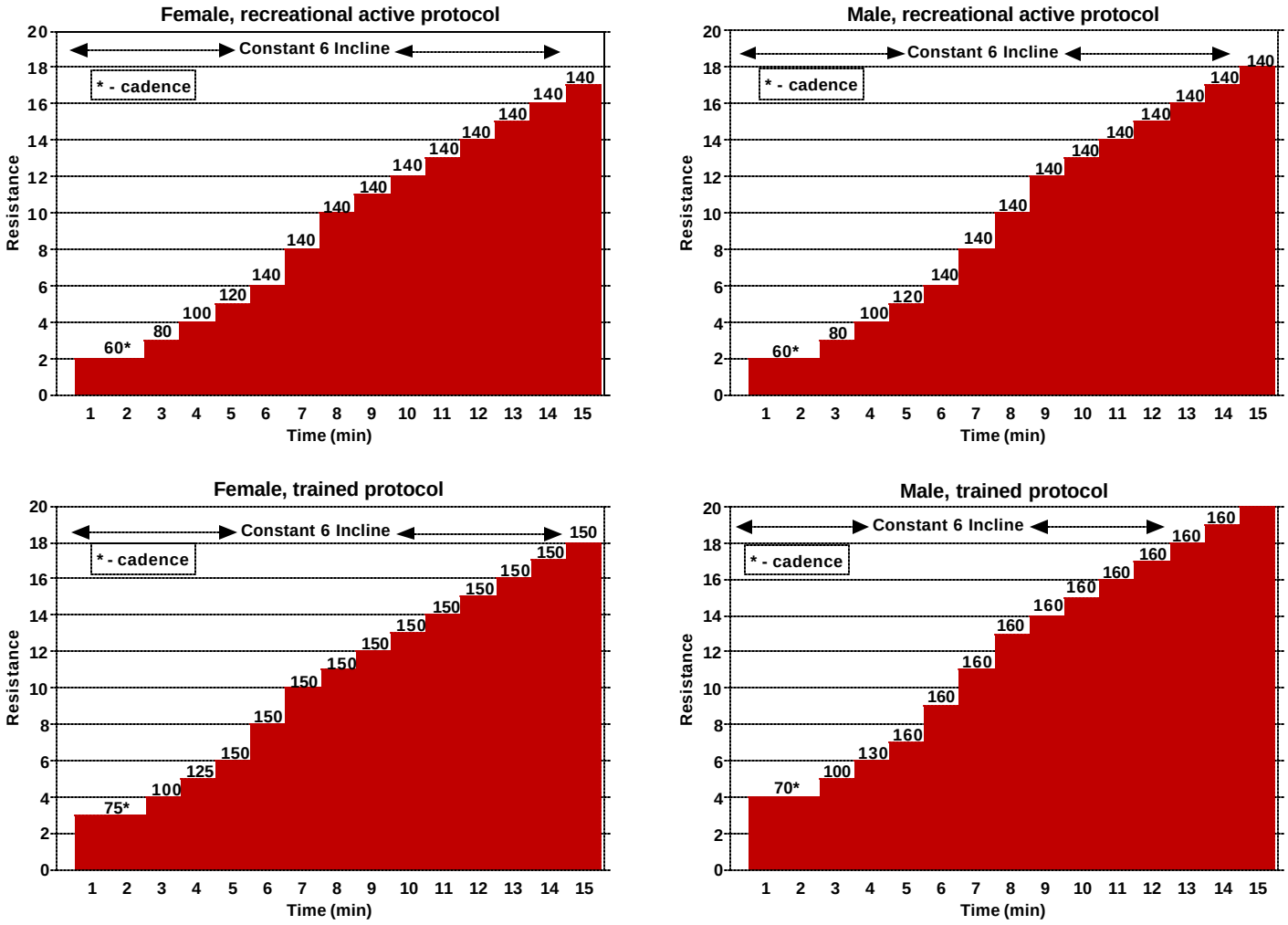


Figure 1. Modified Balke treadmill VO_2max protocol.

Figure 2. Elliptical cross-trainer VO_2max protocols.



Elliptical cross-trainer protocol

After pre-screening and interviewing each subject, a specific elliptical cross-trainer VO_2max protocol (Figure 2) was selected based on gender and aerobic activity participation: trained (aerobic exercise 3-5 hrs/wk) and recreationally active (aerobic exercise 2-3 hrs/wk). After measuring resting expired gases for 2 min, a 2 min warm-up was performed at a light workload prior to the start of the exercise protocol. An incremental protocol was used in which the workload increased in strides/min and/or resistance/min, with incline (slope) remaining at level 6 during the entire test. A metronome was used to assure a consistent and correct stride cadence. The criterion for termination of the exercise test was failure of the participant to maintain within 20 strides/min of the target cadence or volitional fatigue. Following all maximal exercise tests (on both modes of exercise) each subject exercised at a self-selected intensity until heart rate recovered to less than 120 b/min.

Metabolic data collection

A nose clip and three-way valve mouthpiece (Hans Rudolph Inc., Kansas City, MO) was worn so that gas exchange data could be recorded and analyzed. During the exercise test, VO_2, VCO_2, V_E, and respiratory exchange ratio (RER) were measured breath-by-breath using a fast response turbine flow transducer (K.L. Engineering Model S-430, Van Nuys, CA) and custom developed software with AEI oxygen and carbon dioxide electronic gas analyzers (AEI Technologies, Model S-3A and Model CD-3H, Pittsburgh, PA). Raw signals were acquired through a junction box and

integrated with a data acquisition card (National Instruments, Austin, Texas) to a computer. All breath-by-breath data were smoothed using a 7-breath moving average as previously recommended by others (22). HR and cardiac cycle were monitored with a 12-lead EKG continuously during exercise.

Maximal oxygen consumption was assessed by the attainment of two out of three of the following criteria: (1) a plateau ($\Delta VO_2 \leq 50$ mL/min at VO_2peak and the closest neighboring data point) in VO_2 with increases in external work, (2) maximal respiratory exchange ratio (RER) ≥ 1.1, and (3) maximal HR within 15 b/min of the age-predicted maximum (220 – age).

Statistical analyses

Paired t-tests compared VO_2max, HR max, and RER max and protocol duration between the two modes of VO_2max testing: treadmill running versus elliptical cross-training. Level of statistical significance was chosen as $p<0.05$. All analyses were performed using Statistical Package for the Social Sciences, Version 10.0 (SPSS, Inc, Chicago, IL). All data are presented as mean ± SD.

RESULTS

All subjects fulfilled at least two out of three of the VO_2max criteria (Table 2). The physiological responses and protocol durations from maximal exercise testing during treadmill running and elliptical crosstraining are presented in Table 3. A comparison of mean VO_2max, maximal HR, and maximal RER values illustrated that there were no significantly different physiological responses to VO_2max testing between the two exercise modalities: VO_2max [$t(19) = 0.584$, $p = 0.566$]; maximal HR [$t(19) = 1.073$, $p = 0.297$]; and maximal RER [$t(19 = -1.738$, $p = 0.206$]. Correlations between elliptical cross-trainer and treadmill VO_2max ($r = 0.77$), maximal HR ($r = 0.79$), and maximal RER ($r = 0.67$) were all significant ($p < 0.05$).

Additionally, there was no significant difference in mean protocol duration [$t(19) = -1.452$, $p = 0.163$] at which subjects completed the two maximal exercise tests. While treadmill running, subjects required an average time of 11.56 min to complete the VO_2max protocol. During elliptical crosstraining, subjects required an average time of 12.17 min to complete the VO_2max protocol. The correlation between elliptical cross-trainer and treadmill running protocol duration ($r = 0.23$) was also not significant ($p > 0.05$).

Table 2. HR, RER, and DVO_2 at VO_2max criteria data for all subjects.

Subject	*PMHR (b/min)*	*ECT MHR (b/min)*	*Criteria*	*TM MHR (b/min)*	*Criteria*	*ECT RER_{max}*	*Criteria*	*TM RER_{max}*	*Criteria*	*ECT DVO_2*	*TM DVO_2*
1	185	183	Yes	181	Yes	1.27	Yes	1.22	Yes	34.9	47.4
2	200	184	No	191	Yes	1.28	Yes	1.24	Yes	27.7	19.9
3	198	194	Yes	189	Yes	1.33	Yes	1.33	Yes	10.4	19.1
4	191	178	Yes	175	No	1.21	Yes	1.23	Yes	0.6	38.3
5	195	182	Yes	186	Yes	1.13	Yes	1.09	No	40.8	1.9
6	187	177	Yes	179	Yes	1.25	Yes	1.21	Yes	9.5	35.6
7	172	159	Yes	163	Yes	1.06	No	1.03	No	36.1	12.5
8	178	176	Yes	180	Yes	1.3	Yes	1.31	Yes	1.9	15.9
9	192	193	Yes	188	Yes	1.2	Yes	1.32	Yes	5	3.7
10	199	183	No	190	Yes	1.22	Yes	1.25	No	14.4	40.7
11	189	188	Yes	195	Yes	1.34	Yes	1.13	Yes	5.9	43.7
12	197	197	Yes	189	Yes	1.37	Yes	1.28	Yes	20.6	18.4
13	195	183	Yes	185	Yes	1.25	Yes	1.16	Yes	11.4	30.1

14	190	185	Yes	182	No	1.24	Yes	1.15	Yes	31.1	9.9
15	188	181	Yes	192	Yes	1.29	Yes	1.28	Yes	48.2	21.9
16	193	191	Yes	185	Yes	1.31	Yes	1.22	Yes	14.4	11.2
17	198	191	Yes	191	Yes	1.29	Yes	1.33	Yes	3.9	23.9
18	190	175	Yes	177	Yes	1.05	No	1.03	No	24.6	12.8
19	187	194	Yes	188	Yes	1.24	Yes	1.34	Yes	10.5	6.4
20	186	191	Yes	199	Yes	1.35	Yes	1.25	Yes	4.1	15.1
Mean	190.5	184.4		185.7		1.25		1.22		17.8	19.6
SD	7.1	8.8		7.7		0.09		0.10		14.3	13.7

PMHR = Predicted HRmax = (220 – age); MHR = Maximal Heart Rate; ECT = Elliptical cross-trainer; TM = Treadmill

Table 3. Comparison of the physiological responses and protocol durations between the elliptical cross-trainer and treadmill.

Mode	*VO_2max (ml/kg/min)*	*HRmax (b/min)*	*RERmax*	*Protocol duration (min)*
Elliptical cross-trainer	*47.3 ± 6.4	*184.4 ± 8.8	*1.25 ± 0.09	*12.17 ± 1.40
Range :Low to High	35.4 – 57.1	159 – 197	1.05 – 1.37	9.60 – 14.72
Treadmill	*47.9 ± 6.8	*185.7 ± 7.7	*1.22 ± 0.10	*11.56 ± 1.60
Range :Low to High	34.0 – 61.5	163 – 199	1.03 – 1.34	8.31 – 13.25

* $p<0.05$ for Elliptical to Treadmill data

DISCUSSION

The present study was undertaken to develop VO_2max protocols for the elliptical cross-trainer and to compare VO_2max values between the treadmill and elliptical cross-trainer. Four separate, gender- and fitness-specific protocols were devised for the elliptical cross-trainer and used in the study for VO_2max testing (Figure 1). To be considered a valid testing protocol, it has been suggested that similar maximal values should be obtained from the newly established protocol when compared to those from the treadmill (10). The current data indicates similar physiological responses, including VO_2max (Figure 3), maximal HR, and maximal RER, during VO_2max testing between the treadmill and elliptical cross-trainer. Additionally, all subjects satisfied at least two out of the three established criteria for valid VO_2max testing during each exercise mode (Table 3). These research findings support the alternative use of the elliptical cross-trainer in obtaining valid VO_2max values for populations similar to those used in the present study.

Although treadmill exercise is generally believed to elicit the highest VO_2max values in untrained and recreationally active individuals, several studies, including the present investigation, have demonstrated similar VO_2max values can also be obtained from other modes of exercise. Comparable VO_2max values were reported between the treadmill (52.6 mL/kg/min) and VersaClimber (53.9 mL/kg/min), a simulated arm-leg climbing device, in collegiate varsity oarswomen and coxswain (12). Likewise, no significant differences were reported between the treadmill (42.6 mL/kg/min) and NordicTrack cross-country ski simulator (42.5 mL/kg/min) in both male and female subjects of varied fitness levels and cross-country skiing experience (10). Bench stepping exercise has also yielded similar VO_2max values compared to the treadmill (23), although it is not the preferred exercise mode in laboratory settings due to the negative work performed during the test and the difficulty of standardization (24). In healthy and physically active (but not mode-specific trained) populations, arm ergometry (30-40% less) and cycle ergometry (10-15% less) exercise consistently yield lower VO_2max values compared to treadmill exercise (25-27).

Data collection in the present study for the elliptical cross-trainer was conducted on the Precor EFX 544 Elliptical Fitness Cross-trainer (Precor, Inc., Woodinville, WA). However, there are other elliptical cross-trainer products being utilized in fitness settings and cardiac rehabilitation facilities besides the model used in the current study. As noted elsewhere, calibration between different models may vary considerably, limiting the application of research findings to the specific model used in the study (10). The workload components of the elliptical cross-trainer include strides/min (or cadence), incline, and resistance. A metronome was used to ensure that the designated cadence for each stage during the VO_2max protocols was performed accurately. Incline was held constant at a setting of level 6 throughout VO_2max testing to eliminate any potential variability in the calibration of the machine that the parameter would have on VO_2max values. However, the calibration for the resistance workload parameter is under the proprietary control of the company and the assumption was made this workload parameter was accurate throughout VO_2max testing.

CONCLUSIONS

The main finding of the current investigation is similar VO_2max values were attained during treadmill running and elliptical cross-trainer in both males and females whom were recreationally active and trained in fitness status. Because of impact differences and the ease of movement involved with the elliptical cross-trainer, this finding may establish considerable opportunities for those working/testing with special populations, including those who are/have elderly, obese, lower-body orthopedic problems, and those with low-back health problems who are uncomfortable with the greater impact of treadmill exercise. However, future research must be performed to determine if the present findings can indeed be extended to older and diseased populations.

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REFERENCES

1. Astorino TA, Robergs RA, Ghiasvand F, Marks D, Burns S. Incidence of the oxygen plateau at VO_2max during exercise testing to volitional fatigue. ***JEP***online 2000;3(4):1-12.
2. Bassett, DR, Howley, ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. ***Med Sci Sports Exerc*** 2000;32:70-84.
3. Blair, SN, Kohl III, HW, Paffenbarger, RS, Clark, DG, Cooper, KH, Gibbons, LW. Physical fitness and all-cause mortality: a prospective study of healthy men and women. ***JAMA*** 1989;262:2395-2401.
4. Blair, SN, Kampert, JB, Kohl III, HW, Barlow, CE, Macera, CA, Paffenbarger, RS, Gibbons, LW. Influences of cardiorespiratory fitness and other precursors on cardiovascular disease and all-cause mortality in men and women. ***JAMA*** 1996;276:205-210.
5. Costill, DL. Metabolic responses during distance running. ***J Appl Physiol*** 1970;28:251-255.
6. McArdle, WD, Katch, FI, Katch, VL. ***Exercise physiology: Energy, nutrition, and human performance*** 5th ed. Baltimore: Lippincott Williams & Wilkins, 2001.
7. Gergley, TJ, McArdle, WD, Dejesus, P, Toner, MM, Jacobowitz, S, Spina, RJ. Specificity of arm training on aerobic power during swimming and running. ***Med Sci Sports Exerc*** 1984;16:349-353.

8. Magel, JR, Faulkner, JA. Specificity of swim training on maximum oxygen uptake. ***J Appl Physiol*** 1974;38:151-155.
9. Wallick ME, Porcari, JP, Wallick, SB, Berg, KM, Brice, GA, Arimond, GR. Physiological responses to in-line skating compared to treadmill running. ***Med Sci Sports Exerc*** 1995;27: 242-248.
10. Haug, RC, Porcari, JP, Brice, G, Terry, L. Development of a maximal testing protocol for the NordicTrack cross-country ski simulator. ***Med Sci Sports Exerc*** 1999;31:619-623.
11. Rundell, KW. Treadmill roller ski test predicts biathlon roller ski race results of elite U.S. biathlon women. ***Med Sci Sports Exerc*** 1995;27:1677-1685.
12. Brahler, CJ, Blank, SE. VersaClimbing elicits higher VO_2max than does treadmill or rowing ergometry. ***Med Sci Sports Exerc*** 1995;27:249-254.
13. Veeger, HEJ, Yahmed, MH, Van der Woude, LHV, Charpentier, P. Peak oxygen uptake and maximal power output of Olympic wheelchair-dependent athletes. ***Med Sci Sports Exerc*** 1991;23:1201-1209.
14. Toner, MM, Sawka, MN, Levine, L, Pandolf, KB. Cardiorespiratory responses to exercise distributed between the upper and lower body. ***J Appl Physiol*** 1983;54:1403-1407.
15. Sawka, MN. Physiology of upper body exercise. ***Exerc Sport Sci Rev*** 1986;14:175-180.
16. Lewis, SF, Taylor, WF, Graham, RM, Pettinger, WA, Schutte, JA, Blomqvist, CG Cardiovascular responses to exercise as functions of absolute and relative workload. ***J Appl Physiol*** 1983;54:1314-1317.
17. Magel, JR, Faulkner, JA. Maximum oxygen uptake of college swimmers. ***J Appl Physiol*** 1967;22:929.
18. McArdle, WD, Glaser, RM, Magel, JR. Metabolic and cardiorespiratory response during free swimming and treadmill walking. ***J Appl Physiol*** 1971;30:733.
19. McArdle, WD, Magel, JR, Delio, DJ, Toner, M, Chase, JM. Specificity of run training on VO_2max and heart rate changes during running and swimming, ***Med Sci Sports*** 1978;10:16.
20. Sweitzer, ML, Kravitz, L, Weingart, HM, Dalleck, LC, Chitwood, LF, Dahl, E. The cardiopulmonary responses of elliptical crosstraining versus treadmill walking in CAD patients. ***JEP***online 2002;5(4):11-15.
21. Buchfuhrer, MJ, Hansen, JE, Robinson, TE, Sue, DY, Wasserman, K, Whipp, BJ Optimizing the exercise protocol for cardiopulmonary assessment, ***J Appl Physiol*** 1983;55:558-564.
22. Robergs, RA, Burnett, AF. Methods used to process data from indirect calorimetry and their application to VO_2max. ***JEP***online 2003;6(2):44-57.
23. Kasch, FW, Phillips, WH, Ross, WD, Carter, JE, Boyer, JL. A comparison of oxygen uptake by treadmill and step test procedures. ***J Appl Physiol*** 1966;21:1387-1388.
24. Heyward, VH (2002). ***Advanced fitness assessment and exercise prescription*** 4th ed. Champaign: Human Kinetics, 2002.
25. American College of Sports Medicine. ***Guidelines for Exercise Testing and Prescription***, 4th ed. Philadelphia: Lea & Febiger, 1991.
26. Balady, GJ, Weiner, DA, McCabe, CH, Ryan, TJ. Value of arm exercise testing in detecting coronary artery disease. ***Am J Cardiol*** 1985;55:37-39.
27. Brooks, GA, Fahey, TD, White, TP, Baldwin, KM. ***Exercise physiology: Human bioenergetics and its applications*** 3rd ed. Mountain View: Mayfield, 2000.