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Comparison of resistance-based walking cardiorespiratory test to the Bruce Protocol

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Abstract

Cardiorespiratory fitness is assessed through graded exercise tests that determine the maximum amount of sustained mechanical work that an individual can perform while also providing health and fitness related information. This manuscript describes a novel method to perform graded exercise tests that uses posteriorly directed resistive forces. The purpose of this investigation is to validate a novel resistance based test in comparison to a traditional speed and incline based test in a cohort of non-impaired individuals. Twenty non-impaired individuals, 8 males, 12 females, mean age 28.4 ± 9.6 , range 20–54 years old. Participants performed two maximal exercise tests. The speed and incline based test used the Bruce protocol and increased treadmill incline and speed every three minutes. The resistance based test used a robotic device interfaced with the treadmill that provided specified horizontal resistive forces at the center of mass calculated to match each Bruce Protocol stage while individuals walked at 1.1 m/s. Participants obtained ~3% higher maximum $\dot{V}O_2$ measure using the speed and incline based method (dependent t-test $p=0.08$). $\dot{V}O_2$ peaks between tests were strongly correlated ($r=0.93$, $p<0.001$). Peak values of secondary physiologic measures (i.e., max heart rate, respiratory exchange ratio) were within 3% between tests. We found a significant linear relationship between mass-specific work rate and measured $\dot{V}O_2$ stage-by-stage for both tests, but no significant difference between each linear fit ($p=0.84$). These data suggest horizontal resistive forces while walking on a treadmill, can be used to increase aerobic effort in a way that closely simulates work rates of the Bruce Protocol.

Keywords

Aerobic Testing; Resistive Force; Walk; Treadmill

INTRODUCTION

Cardiorespiratory fitness is assessed through graded exercise tests that determine the maximum amount of sustained mechanical work that an individual can perform. Graded exercise testing is useful for creating individualized exercise prescriptions, grading of the etiology and severity of an impairment, for instance in heart failure patients, risk stratification, and an accurate and reproducible assessment of the response to an exercise intervention to improve cardiorespiratory fitness and health (11, 15). Thus, the use of maximal aerobic tests has been encouraged in a number of healthy and clinical populations (3, 11, 15)

Treadmill-based tests can be difficult for deconditioned individuals or those with gait and balance impairments. This is due to gait limitations such as a limited range of walking speeds or gait instability that interacts with the methods of treadmill testing to elicit a maximum effort. Treadmill-based methods of assessing cardiorespiratory fitness progressively increase the treadmill belt speed and grade or slope of the treadmill surface (11) to increase the mechanical work that must be done by the person on their center of mass (COM) to maintain their position on the treadmill. Concern of falling off the back of the treadmill may limit effort or motivate the use of handrails while performing these maximal exertion tests on a progressively increasing slope (19). Thus, other modalities like bicycle or arm ergometers are utilized, or alternatively, submaximal tests are used (3). However, ambulatory tests using walking and/or running result in the most accurate assessments of $\dot{V}O_{2\max}$. In fact, other testing modalities like bicycle ergometers or handrail assistance while walking or running, can result in significant error in assessing $\dot{V}O_{2\max}$ i.e., 10–30% (4, 7, 8, 16, 24). Clinicians and other healthcare providers need a novel way to perform exercise testing that considers gait and balance limitations so $\dot{V}O_{2\max}$ can be accurately assessed.

Application of posteriorly directed resistive force at an individual's COM while walking on a treadmill offers an alternative to increasing the slope and speed of the treadmill surface to progressively increase work rates. Application of posteriorly directed forces to individuals have previously been used to study fundamental aspects of locomotion in impaired and nonimpaired populations. Recently we have used posteriorly-directed resistive forces to assess characteristics of self-selected walking speed of individuals poststroke and nonimpaired control participants. All individuals tolerated walking against relatively high posteriorly directed resistive forces without external aids to stabilize themselves like handrails (17, 29). Previous research in healthy young adults has also shown that the rate of oxygen consumption increases linearly while walking and experiencing posteriorly directed resistive forces at the level of the COM (13). Additionally, non-impaired individuals had similar efficiencies and metabolic rates when walking on a sloped treadmill to those while walking on a level treadmill at a constant speed while experiencing posteriorly directed resistive forces (10). However, individuals locomoted at the same speed between the two

conditions in the latter investigation. It is also possible to fix walking speed on level treadmill and match externally applied work rates with the sloped treadmill condition by adding horizontal resistive force.

This manuscript describes a novel method to perform graded exercise tests that uses posteriorly directed resistive forces. This resistance-based test (RBT) increases externally applied work rates by increasing posteriorly-directed resistive forces while keeping the treadmill belt speed constant. In contrast, the traditional speed and incline-based test (SIBT) progressively increases the grade and speed of the treadmill. The purpose of this investigation is to validate the RBT in comparison to a traditional SIBT in a cohort of non-impaired individuals. We hypothesized that the RBT would result in $\dot{V}O_{2peak}$ values that were comparable to SIBT, and further, that there would be a significant correlation between test measures at different stages of work rates. We also expected that we would be able to match work rates stage-by-stage between the two tests, as evidenced by similar physiologic responses.

METHODS

Experimental Approach to the Problem

To test our hypothesis, we employed a repeated measures study design. All participants performed two maximum graded exercise tests separated by at least 48 hours, but no more than one week. $\dot{V}O_{2peak}$ was a primary dependent variable for this study as a quantitative endpoint to assess peak cardiorespiratory fitness. Secondary outcome measures included other physiologic variables that characterize these maximum exertional tests such as respiratory exchange ratio, maximum observed heart rate, and time to complete both tests.

Subjects

Twenty non-impaired individuals, 8 males, 12 females, mean age 28.4 ± 9.6 , range 20–54 years, height 1.71 ± 0.09 m, mass 67.51 ± 3.34 kg volunteered to participate in this study. Participants were screened using the AHA/ACSM Health/Fitness Facility Pre-Participation Screening Questionnaire. Individuals were included only if they did not select any items assessing cardiovascular history (e.g., previous heart attack), symptoms (e.g., chest discomfort), and other health issues (e.g., musculoskeletal problems, diabetes), and if they selected no more than one cardiovascular risk factor. Participants also filled out a PAR-Q as part of the consent process. All participants provided written informed consent prior to participation, approved by the University of Alabama at Birmingham Institutional Review Board.

Procedures

For both testing days, participants were instructed to not eat any solid food three hours before each test, but were allowed to hydrate with water. The SIBT was conducted using the Bruce Protocol (6), in which relative required power outputs or work rates were progressively increased in 3-minute stages (Table 1). The SIBT was conducted on a standard treadmill (Trackmaster, Full Vision Inc. Newton, KS); thus, work rates were increased by a

combination of increasing treadmill speed and the incline of the treadmill surface according to the protocol.

Individuals performed the resistance-based test (RBT) while maintaining a walking speed of 1.1 m/s against progressively increasing posteriorly directed resistive forces. This speed was chosen because it is slightly slower than the comfortable walking speed of healthy adults (5), and therefore should be relatively easy to maintain throughout the test. We used a custom algorithm to select the appropriate stage-by-stage posteriorly directed resistive forces based on theoretical mass-specific work rates of the Bruce Protocol performed as a SIBT (Table 1). We applied resistive forces in the RBT via a rehabilitation robotic device (KineAssist, HDT Global Salon, OH, Fig. 1) that is partnered with a treadmill (Woodway Waukesha, WI). The device is designed for balance and mobility training of individuals (23). For this study we manipulated the device's software to create a resistive force walking condition used to match external work rates of the Bruce Protocol. The device interfaces with individuals through a pelvic mechanism that uses bilateral force transducers to measure the horizontal forces that an individual generates against the pelvic mechanism. The force signal is used to generate a command signal to the treadmill to move the belt at a proportional speed making this system self-driven, that is, the individual can intentionally select the treadmill belt speed. We can manipulate the magnitude of average force to achieve a specific velocity via a software interface, thereby creating posteriorly directed resistive forces (17). We provided individuals with a target speed on a screen (10.1×15.2 cm) adjustable to eye level (Fig. 1). The speed target consisted of upper and lower limits, which were $\pm 20\%$ of the target walking speed, because walking velocity fluctuates in the robotic device as it does over ground. We instructed individuals to maintain their velocity within this range (Fig 1). All participants were acclimated to walking in the device before we initiated the RBT. Testing began when participants affirmed that they felt comfortable in the device and could control their walking speed.

Both tests were terminated based on based on contraindications (ACSM Guidelines), or if participants voluntarily stopped the test. For the RBT, we added a final criterion. If individuals could not maintain the prescribed walking speed (i.e., 1.1 m/s), they were provided with verbal encouragement to increase their speed and if they were unable to do so we terminated the test to ensure that individuals were testing under the same work rates. We measured physiologic responses to the exercise tests via indirect calorimetry (Cortex Medical Leipzig, Germany). We calibrated the device before each test based on manufactures recommendations. We averaged data over 30-second increments (25). We selected the last 30-second sample in each stage, to assess stage-by-stage data, except for the stage in which individuals ended the test. For that stage, we used the data from that 30-second increment. We monitored heart rate, blood pressure, and rating of perceived exertion (RPE) throughout the test.

Statistical Analysis

To measure the extent of agreement between the RBT and the SIBT for the primary dependent variable, $\dot{V}O_{2peak}$, we performed a Pearson-r correlation. To test whether differences existed between achieved, $\dot{V}O_{2peak}$ we performed a dependent t-test. We

compared secondary variables, including heart rate max (HR_{max}), respiratory exchange ratio (R.E.R.), rating of perceived exertion (RPE) and time to completion of each test with a dependent t-test. To assess the extent to which work rates were similar stage-by-stage, we performed a linear regression between $\dot{V}O_2$ values and the stage specific theoretical work rates. We assessed any interaction between stage-specific work rates and test condition with a dummy-coded term in the equation. Peak $\dot{V}O_2$ has been shown to be highly reliable in healthy nonimpaired individuals along with patient populations with ICCs 0.96 (2, 4). We performed all statistical tests using SPSS 22.0 (IBM, Armonk NY) with a threshold p-value <0.05 for significance.

RESULTS

All but one participant completed both exercise tests to voluntary fatigue. One RBT was ended abruptly due to a mechanical fault of the device. For that individual, we still included the stage-by-stage data of the completed stages in analyses. Thus, data included in the maximal exercise tests was $n=19$, while for the stage-by-stage data $n=20$. For the RBT maximal test, 8 of 19 tests resulted in an increase in work rate, and failure for $\dot{V}O_2$ to increase > 2.1 ml/kg/min (28). By comparison, 6 of 19 of these $\dot{V}O_2$ plateaus occurred in the SIBT test. We also quantified secondary criterion measures to determine a true $\dot{V}O_2$ max. Eleven of nineteen RBTs resulted in an R.E.R of >1.10 (1), while 13 of 19 SIBT tests resulted in an R.E.R of >1.10. Finally, for the RBT, measured HR max was $-3.1\% \pm 7.4\%$ from the predicted HR max (27), while the SIBT resulted in HR max that was $-0.6\% \pm 5.3\%$ from predicted HR max.

For both tests, we observed close agreement in physiologic variables related to $\dot{V}O_{2peak}$. For the RBT, mean $\dot{V}O_{2peak}$ was 42.0 ± 5.9 ml/kg/min while the same individuals performing the SIBT achieved an $\dot{V}O_{2peak}$ of 43.0 ± 6.8 ml/kg/min ($p=0.08$). There was also a strong and significant correlation between the two tests ($r=0.93$ $p<0.001$, Fig. 2). Interestingly, some individuals ($n=7$) achieved a marginally higher $\dot{V}O_{2peak}$ for the RBT as compared to the SIBT (Fig. 3). We found no statistical difference for HR peak between tests. The mean value for the RBT was 183.0 ± 13.3 beats per minute (bpm), as compared to 188.1 ± 11.3 bpm for the SIBT ($p=0.08$). We observed a significant difference for the R.E.R. The mean value for the RBT was 1.10 ± 0.03 , and for the SIBT the mean was 1.13 ± 0.05 ($p=0.009$). We also observed a significant difference in the RPE at test completion. The mean value for the RBT was 16.9 ± 1.6 , and for the SIBT the mean was 17.5 ± 1.3 ($p=0.04$). There was also no significant difference between tests for the time to completion of each test. The mean time to completion for the SIBT was 12.86 ± 1.86 min, and for the RBT it was 13.35 ± 1.86 min ($p=0.008$).

Regarding the stage-by-stage analysis of $\dot{V}O_2$, we found a significant correlation between RBT and stage-specific work rate ($r=0.94$, $p<0.001$), and a significant linear correlation for the SIBT and stage-specific work rate as well ($r=0.96$, $p<0.001$). The overall regression model fit was significant ($p<0.001$). Beta coefficients for stage-specific work rate and measured $\dot{V}O_2$ were significant ($p<0.001$), but the interaction between work rate and test (RBT vs. SIBT) was not significant ($p=0.84$). The equation for the model was $Y=9.8 * \text{Work Rate}_{\text{stage specific}} + 9.98$. The 95% confidence intervals of $\dot{V}O_2$ on a stage-by-stage basis were

closely aligned for stages two through five (see table 2). Stage one resulted in a higher $\dot{V}O_2$ for the RBT test compared to SIBT.

DISCUSSION

The purpose of this investigation was to validate the RBT in comparison to a traditional SIBT in a cohort of non-impaired individuals. We hypothesized that the RBT would result in $\dot{V}O_{2peak}$ values that were comparable to SIBT, and further, that there would be a significant correlation between test measures at different stages of work rates. We also expected that stage-by-stage, we would be able to match work rates between the two approaches, as evidenced by the physiologic response. In support of our hypotheses, the RBT resulted in $\dot{V}O_{2peak}$ values that were ~2.5% less than SIBT in a group of healthy adults, and further, the data were strongly correlated suggesting a similar test-retest response. Several secondary physiologic responses were also similar between tests, all within 3% of each peak value. Finally, we observed a similar relationship between tests for the stage-by-stage mass-specific work rates and measures of $\dot{V}O_2$.

The results of our investigation suggest that we were able to match peak work rates between the RBT and SIBT. Physiologic variables were all within 3%. Reliability of standard repeated $\dot{V}O_{2peak}$ tests fall within this range (21). The close agreement between these tests may be surprising despite the fact that the theoretical work rates were the same between tests. We highlight three points that could have resulted in a greater discrepant $\dot{V}O_2$ between these tests. First, most individuals reached the fourth stage of the Bruce protocol (~1.9 m/s, 16% incline), which results in individuals choosing a slow jog uphill. Our method of estimating work did not account for work that is done to swing the limbs at faster speeds, which is reported to be higher than walking (30). Second, as individuals walk/run at faster speeds, differences in the magnitude of vertical oscillations of the COM are observed (14, 20, 22). For instance, as individuals walk at faster speeds, there is an increase in vertical oscillations of the COM. Further, at increasing slopes while walking or running, greater mechanical energy must be generated to raise the COM (14, 26). We did not account for increased vertical work on the COM in our equation for estimating total work performed by the system for hill locomotion. Third, gluteus maximus activity is higher for running compared to walking (18), and increases in a nonlinear fashion as the slope of the surface increases (12). Despite these potential factors, we still observed close agreement in our physiologic outcome measures. Future investigations should determine the kinematic differences between the two tests and how they relate to muscular activation patterns and kinetics. The similarity between these two tests suggest that resistive forces can be used as a valid method of assessing $\dot{V}O_{2peak}$.

In the current investigation, we report no difference in the slopes of the regression lines between $\dot{V}O_2$ values and the theoretical relative work rates. This would suggest that stage-by-stage work rates were similar between the two tests. Stage-by-stage, (see table II) the $\dot{V}O_2$ values for stage three through five were within overlapping 95% confidence intervals, while stage 2 $\dot{V}O_2$ was within 8.7% of each other. We reported a large relative difference in $\dot{V}O_2$ values of stage one for both tests (~3.6 ml/kg/min). The walking speed for the RBT was 1.1 m/s, while the walking speed for stage one of the SIBT was 0.76m/s. While fore-aft

work rate was theoretically equivalent, it is possible that the faster walk speed could have caused aforementioned increases in mechanical work for the RBT tests. Another possibility is that the reported difference could be related to the testing device used for the RBT. Our previous research demonstrates that kinetic differences exist between walking in the device and walking outside the device, which may result from the interaction of the individuals with the pelvic mechanism (9). These differences primarily related to increased hip extension moments at heelstrike, which caused a larger loading-phase ground reaction force peak. We would expect such a difference to be consistent throughout the test; however, the stage-by-stage difference in $\dot{V}O_2$ between tests was not consistent. Stages one and two showed a larger $\dot{V}O_2$ value for the RBT, while stages three, four and five resulted in higher $\dot{V}O_2$ values for the SIBT. We carried out the current investigation on a non-instrumented treadmill; thus, we did not have the benefit of a full kinetic analysis, and were unable to resolve this issue. However, the current investigation also provides some validation that use of posteriorly directed resistive forces could be used to as a novel way to perform exercise training.

Current standardized treadmill tests of aerobic fitness may be difficult for individuals with gait and balance disability to perform (3). However, the RBT allowed us to match existing tests, while allowing individuals to walk at their own comfortable constant walking speeds with a 0% grade. Thus, the RBT may be useful for individuals who may not be able to perform traditional peak exercise tests due to gait or balance disability. Previous research suggests that individuals with gait and balance disability are able to walk against high relative amounts of resistive forces despite their slow walking speed and limited range of walking speeds (29). Further, these individuals tolerated the backward directed resistive forces without the use of handrail support and walked self-selected walking speeds that would suggest that these forces were not destabilizing to balance (17). Performing peak exercise tests using posteriorly directed resistive forces has an advantage over alternative tests that may underestimate $\dot{V}O_{2peak}$ of individuals (4, 8, 24). Further, while we were able to closely approximate the $\dot{V}O_{2peak}$ for all individuals, of particular note is how the data suggests that individuals with lower $\dot{V}O_{2peak}$ s (Fig 2) recorded higher $\dot{V}O_2$ on our RBT compared to the SIBT. In fact, 5 of the 7 individuals who reached a nominally higher $\dot{V}O_{2peak}$ while performing the RBT were at or below the average $\dot{V}O_2$ value for the SIBT of 43 ml/kg/min. Anecdotally, we asked individuals to compare both tests as an open-ended question. Some individuals suggested that while the RBT felt easier to perform the RBT resulted in more lower extremity localized fatigue then the SIBT. However individuals also felt the RBT was safer because they didn't have to run uphill and thus didn't worry about falling off the back of the treadmill. Future research will test if this method of exercise testing is efficacious for individuals with gait and balance disability.

The current investigation used an innovative and sophisticated rehabilitation robotic device. However, this device is very specialized and may not be widely available to exercise physiologists and clinicians performing exercise tests. The overarching purpose of this manuscript was to validate a novel method for using posteriorly directed resistive forces to administer a maximal exercise test, the application of which can be administered in multiple forms as long as the applied force can be controlled. Posteriorly directed resistive forces

could also be applied with elastic materials like rubber tubing (13), or by a cable attached to a constant torque motor (31).

There are limitations with the current investigation. First, all participants walked at 1.1 m/s for the RBT, even though our method allowed individuals to self-select any walking speed, and subsequently model any traditional exercise test. Since we were validating the extent to which a $\dot{V}O_{2peak}$ could be elicited by a walking test, we wanted to control the walking speed. The walking speed we selected is similar to reported comfortable walking speeds of otherwise healthy individuals. However, preliminary data in our lab suggests that our method is also robust for individuals walking at a variety of walking speeds. Second, we did not systematically randomize the presentation of the two tests. While some individuals performed the RBT first, the majority of participants first performed the SIBT. We reported that seven individuals achieved a higher $\dot{V}O_{2peak}$ while performing the RBT. Five of these individuals performed the SIBT first. This may indicate a learning effect in these participants. However, the difference between measured $\dot{V}O_{2peak}$ for the majority of the participants was 6% or less, which is the range of test-retest reliability in peak exercise testing (21). Thus, we do not feel that much of a learning effect could have occurred.

Practical Applications

These data suggest posteriorly directed resistive forces applied at an individual's COM as they walk at a constant comfortable walking speed is a valid way to increase aerobic effort in a way that closely simulates work rates of the Bruce Protocol. This method could be modified to any other standardized exercise test while individuals walk at their own comfortable speed. Also, while a robotic device was used in this investigation, progressive posteriorly-directed resistive forces could also be applied with elastic materials like rubber tubing (13) or a gravitational load (10) applied at an individual's waist while walking. Further, the close agreement in stage-by-stage data suggests that prescribed work rates, based on an individual's walking speed, could be a valid way to prescribe individualized aerobic training for individuals with gait and balance disability with whom walking speed may be limited making the performance of standard graded exercise tests problematic or traditional treadmill training difficult. For instance, individuals with lower limb orthopedic issues could exercise at a slower walking speed but still have the benefit of a cardiorespiratory stimulus. We have demonstrated that individuals with gait and balance impairment can safely tolerate walking while experiencing backward directed forces (17, 29). Thus, the method described for exercise testing presents a novel way to accurately assess cardiorespiratory fitness on a treadmill by individuals with limitations that may preclude traditional treadmill tests.

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Figure 1.

Example of the experimental setup for the resistance-based tests that used a rehabilitation robot. Individuals were asked to maintain an average walking speed of 1.1 m/s throughout the duration of the test. The device allows for fluctuations in walking speed, similar to that seen during normal overground walking; thus, individuals were provided a targeted range within which they maintained the speed trace of the treadmill belt (A). The resistive force that the participant must overcome is also depicted on this screen (e.g., 53 lbs pictured in the upper left corner of A.). The participant controlled speed of the treadmill belt based on measured forces (i.e., via bilateral force transducers) embedded in the pelvic mechanisms (B) and a linear, force-velocity relationship.

Figure 2.

The relationship between repeated peak exercise tests using a speed and incline based test (SIBT) and a resistance based test (RBT). We observed a strong linear relationship between tests. The tests did not align perfectly with the line of identity (dark black line).

Figure 3.

Differences in peak $\dot{V}O_2$ between tests as a percentage. We observed that 7 individuals nominally achieve a higher $\dot{V}O_{2peak}$ using the resistance based test. The average difference between test, pictured at the end of the bar chart was ~2.5%.

Table 1

Theoretical mass-specific work rates of the Bruce Protocol. We quantified the level of resistance for the resistance-based test using these work rates.

Bruce Protocol			
Stage	Treadmill Speed (m/s)	Percent Grade	Theoretical Work Rate (W/kg)
1	0.74	10	0.74
2	1.12	12	1.31
3	1.52	14	2.07
4	1.88	16	2.91
5	2.24	18	3.88
6	2.46	20	4.73

Table 2

Means and 95% confidence intervals (C.I.) for quantified $\dot{V}O_2$ (ml/kg/min) on a stage-by-stage basis for the speed and incline-based test (SIBT) and the resistance-based test (RBT).

Stage	1	2	3	4	5
SIBT	15.2	21.8	31.1	41.2	47
95% C.I.	14.5–15.9	20.9–22.7	30.0–32.2	30.0–43.4	45.5–48.9
RBT	18.9	23.7	31.7	39.4	45.0
95% C.I.	18.0–19.8	–22.7–24.7	30.1–33.2	37.2–41.5	42.3–47.7