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Validation of a Novel VO2max Protocol

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VALIDATION OF A NOVEL VO_{2MAX} PROTOCOL

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Table of Contents

VALIDATION OF A NOVEL VO_{2MAX} PROTOCOL

Griffin Green May 2020 48 pages

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Though there are several to choose from, the Bruce protocol is the most commonly utilized treadmill protocol when assessing maximal oxygen consumption (VO_{2max}). Originally developed for cardiac patients, the Bruce protocol may not be an appropriate treadmill protocol for young or trained individuals with higher levels of cardiorespiratory fitness. The steep grade used often leads localized muscular fatigue, which may cause participants to end the test prior to reaching their true VO_{2max}. Another popular protocol, the Astrand, also utilizes a steep grade, but the speed remains constant. Similar to the Bruce, the Astrand protocol may not prompt a maximal cardiovascular response in healthy individuals. Though validated, these tests may have inherent limitations resulting in an underestimation of VO_{2max} in healthy or well-trained populations. The purpose of this study is to validate a novel VO_{2max} protocol that may be better suited for healthy, well-trained populations by starting at a higher intensity and reducing the initial grade to limit lower extremity fatigue. Fifteen participants performed the Bruce, Astrand, and Novel protocols with the following maximal values being recorded from each protocol: VO_{2max}, maximal ventilation (VE_{max}), respiratory exchange ratio (RER), heart rate (HR), rating of perceived exertion (RPE) and time to exhaustion (TTE). Bland-Altman analysis revealed that the Novel protocol exhibited a low degree of bias with tight limits of agreement when

compared to the Bruce (bias ±95% LOA = 0.824 ± 3.163) and Astrand protocols (-0.153 ± 3.528) for VO_{2max}. A paired samples t-test revealed no significant differences between Novel and criterion protocols for VO_{2max}. Paired samples t-test revealed that the Novel protocol resulted in significantly lower TTE when compared to the Bruce and Astrand protocols. The Novel protocol produces similar VO_{2max} values to that of the Bruce and Astrand protocols with lower TTE, and thus a shorter test duration, making it a more time-efficient protocol for this population.

Introduction

Maximal oxygen consumption (VO_{2max}) is defined as the maximal amount of oxygen that an individual can bring in and utilize within active tissues in one minute. It is generally the accepted measure to determine an individual's cardiorespiratory fitness and functional capacity of the heart. For these reasons, poor cardiorespiratory fitness is indicative of physical inactivity and are associated with increased risk cardiovascular disease and all-cause mortality (1).

In healthy and athletic populations, VO_{2max} is often used to assess the capacity to compete in aerobic or endurance events (1). A high VO_{2max} is the result of both central and peripheral adaptations to the respiratory, cardiovascular, and musculoskeletal systems. Whether mechanical or cellular, the adaptations within the different systems work to complement one another to improve an individual's ability to transport oxygen to the working musculature, effectively extract it from the blood and use it in cellular respiration. In addition to assessing cardiorespiratory fitness and aerobic capacity, an accurate measurement of VO_{2max} allows athletes to track progress, monitor and manipulate their pacing, and help them in predicting future performances (1,10).

VO_{2max} is most commonly assessed on the treadmill for many reasons; [1] running is a familiar form of exercise in athletic performances; [2] running is a full body, weight bearing activity that requires high levels of muscle mass utilization (1). Numerous treadmill protocols have been developed in an attempt to challenge the oxygen transport system and while minimizing the likelihood of exercise cessation due specifically to localized muscular fatigue. These protocols manipulate speed, grade, and stage duration to allow a participant to perform at their maximal aerobic capabilities. However, each treadmill protocol has limitations when applying to subgroups of populations and those with wide ranges of aerobic capabilities. These application issues may introduce measurement error and a potentially flawed VO_{2max} measurement.

There are many graded exercise tests from which practitioners may choose. The Bruce and Astrand are two validated protocols, often used in research and applied settings. The Bruce modifies speed and grade every three minutes, while the Astrand is set to an unchanging (or at a constant) speed and modifies the grade every two minutes. In the United States, the Bruce is the most widely used protocol to assess VO_{2max} in healthy and athletic populations (7,16,21). However, this protocol was originally developed to screen symptomatic patients for coronary artery disease, arrhythmias, and other cardiac complications (6,21). Because the original population mostly consisted of middle-aged men with congenital heart abnormalities (6,21), the first stages of the Bruce protocol are a very low intensities (walking) to minimize risk and acutely identify the presence of a cardiac complication. The first stages are largely unnecessary when testing populations for functional fitness, not cardiovascular symptoms. The steep grade utilized in the latter stages of the Bruce protocol may induce excessive localized muscular fatigue in the lower extremities, leading to an underestimation of VO_{2max} in healthy and well-trained participants (7,16).

The Astrand, an alternative to the Bruce, has a speed of five miles per hour for the entire duration of the test, which may be abnormally slow for athletic populations. Additionally, the first stage of the test is at a 0% grade, which does not control for wind resistance or treadmill inertia (14). Similar to the Bruce protocol, the intensity during the first stage of the Astrand protocol may also be too low, which may suggest that a protocol beginning at a higher intensity may be optimal for healthy and athletic populations. The limitations of these two validated tests can induce measurement error and underestimation of VO_{2max} in healthy or well-trained populations. It may be postulated that a treadmill test with lower starting grades and higher starting speeds would better assess those who are physically active.

Statement of Purpose

The purpose of this study is to validate a novel VO_{2max} protocol that may be better suited for healthy or well-trained populations. Secondly, this protocol may present fewer limitations, a reduced chance for measurement error, a reduced time to exhaustion, and be preferred by participants.

Hypotheses

H_{o1}: The Novel protocol will produce cardiorespiratory and metabolic values that are not significantly different from the Bruce and Astrand protocols.

H_{a1}: The Novel protocol will produce cardiorespiratory and metabolic values that are significantly different from the Bruce and Astrand protocols.

H_{o2}: The Novel protocol will produce RPE values that are not significantly different from the Bruce and Astrand protocols.

H_{a2}: The Novel protocol will produce RPE values that are significantly different from the Bruce and Astrand protocols.

H_{o3}: The Novel protocol will produce TTE values that are not significantly different from the Bruce and Astrand protocols.

H_{a3}: The Novel protocol will produce TTE values that are significantly different from the Bruce and Astrand protocols.

Delimitations

- Participants were males and females, 18-28 years old
- Participants were non-smokers
- Participants performed planned, structured physical activity ($\geq$ 30 min, $\geq$ 3x per week)
- Participants did not have any known cardiovascular, pulmonary or metabolic diseases
- Participants had no major signs or symptoms suggestive of cardiovascular, pulmonary or metabolic diseases
- Participants completed three maximal graded exercise tests

Limitations

- Changing out of Parvomedics carts due to a malfunction on the TrueOne Metabolic Analyzer circuit board
- Small sample of convenience
- Abrupt end to data collection due to university closure and discontinuation of face to face data collection
- Varying cardiorespiratory fitness level between participants
- Dietary intake of participants prior to sessions was not controlled
- Body composition data are missing from some participants

Definition of Terms

- *Maximal oxygen consumption (VO_2max)* - maximal amount of oxygen consumed per minute during exercise; it is a product of cardiac output and arterial-venous oxygen difference.
- *Cardiorespiratory Fitness (CRF)* - ability to perform large muscle, dynamic, moderate-to-vigorous intensity exercise for prolonged periods of time.
- *Maximal Ventilation (VE_{max})* - maximal amount of air moved through the lungs in one minute.
- *RER (Respiratory Exchange Ratio)* - a ratio of expired CO_2 to inspired O_2.
- *Time to Exhaustion (TTE)* - duration of a graded exercise test from start to volitional exhaustion and stopping the test.
- *Heart Rate (HR)* - number of times your heart beats per minute.
- *Miles per Hour (mph)* - unit of speed expressing the number of statute miles covered in one hour.

Literature Review

Introduction

The Bruce protocol was the first multistage treadmill protocol used to assess cardiovascular hemodynamic changes in exercising patients (6). Bruce et al. (1963,6) were the first to consider the importance of assessing maximal oxygen uptake (VO_{2max}) and exercise tolerance in cardiac patients. They determined these variables to be just as critical as the electrocardiogram and heart rate changes that occurred during an exercise test. Prior to their research, it was understood that maximal exertion was necessary in order to assess the ability of the oxygen transport system. However, practitioners deemed maximal exercise testing for clinical purposes too dangerous for clinical populations (6).

Out of necessity, the Bruce protocol was developed to gradually progress cardiac patients from a submaximal and increasing workloads to a self-determined point of maximal exertion. Practitioners were now able to utilize a validated protocol to evaluate and monitor exercise tolerance and aerobic exercise capacity in healthy populations, while also screening symptomatic patients for coronary artery disease, arrhythmias, and other cardiac complications (6,21).

From their research, Bruce et. al (1963,6) observed that healthy patients were typically able to reach the third stage, but very few clinical patients could do so before cardiovascular complications were present. It was discovered that the first stage (1.7 mph, 10% grade) was the maximal workload for 18% of cardiac patients, while none of the healthy participants were limited at this point. This early workload was considered a moderate intensity for healthy individuals and cardiac patients with minimal impairment. Those with severe cardiovascular impairments perceived this workload as maximal and were not able to maintain this workload for ten minutes. Having been developed for clinical purposes, the first two stages of the Bruce protocol are set at a low intensity. Therefore, early intensities may be considered a warmup or simply not necessary for those of normal or high levels of cardiovascular fitness.

In the United States, the Bruce Protocol continues to be routinely used with healthy and athletic populations to assess VO_{2max} during graded exercise tests (21). However, the Bruce protocol may not be appropriate for healthy and/or athletic populations when the purpose of the graded exercise test is to determine aerobic performance. This review will attempt to evaluate the ability of other standardized/validated and novel treadmill protocols to elicit VO_{2max} values that are validated by those of the Bruce protocol.

Analysis and Discussion

For individuals of higher fitness levels, it has been suggested that the Bruce protocol may underestimate VO_{2max} and result in test durations that exceed the optimal durations. For these reasons, the following subsections will attempt to address the flaws of the Bruce protocol for healthy and athletic populations, while providing evidence in support of or against the alternative treadmill speeds, grades, and test durations used in other validated or novel treadmill protocols.

Incremental Speed

Early stages of the Bruce protocol are identified with steep treadmill inclines (starting at 10%) and slower speeds (beginning with 1.7 mph). Even with significant incline, a jogging speed is not reached until the third stage (3.4 mph), six minutes into the test. Anecdotally, taller individuals may not jog until the fourth stage (4.2 mph) or nine minutes into the test. It has been suggested that the pronounced inclines used during the Bruce protocol produce fatigue in the lower extremities and that participants may end the test due to muscular fatigue prior to achieving maximal cardiorespiratory performance (16). Few protocols remain at a specific grade and only manipulate speed throughout the test.

Duff et al. (2017,7) developed a novel protocol that has an initial speed and grade of 2.0 miles per hour (mph) and 1%, respectively. This protocol increases 0.5 mph every minute until the participant reaches volitional fatigue. It was believed that holding grade to 1% would limit peripheral fatigue of the lower extremities, thus allowing participants to achieve maximal performance values (7). The protocol did not produce significantly different values for VO_{2max}, VE, RER, and HR when compared to the Bruce protocol. However, the new protocol averaged longer times to exhaustion (15:15 vs 13:30 min). A previous study by Nordrehaug et al. (1991,17) confirms these results after testing a similar incremental speed and constant grade protocol. While grade remained at 0%, initial speed was set at 1.24 mph and increased 1.24 mph every third minute. Once again, the results revealed no significant difference in VO_{2max}, VE, and RER when compared to the Bruce protocol. However, the protocol developed by

Nordrehaug et al. (1991,17) did result in significantly longer times to exhaustion when compared to the Bruce protocol (21.8 min vs 13.35 min). It appears that in an attempt to limit fatigue, these protocols were too conservative and did not challenge the muscular or cardiovascular systems until the participants were well into the exercise test.

The longer times to exhaustion observed by the first two studies suggest that the protocols started at speeds that were too slow for their participants (2.0 and 1.24 mph). With minimal grade, the speed of these protocols' first few stages needed to be significantly faster than those of the Bruce protocol to elicit a similar, or even greater workload. It may be beneficial to remove the first stages or start at higher speeds to reduce the times to exhaustion and the complications that come with test durations that are too long.

Two strategies can be implemented to reduce time to exhaustion (TTE): use higher speed increments for each stage and/or reduce the duration of each stage. Comparing two incremental speed protocols, Billat et al. (1996,4) determined that employing increments of 0.62 mph every two minutes resulted in greater TTE than increments of 0.31 mph every minute (16.5 vs 15.6 min). These small differences in speed increments from stage to stage did not impact the determination of VO_{2max}. However, it is important to note that Bilat et al. (1996,4) began their incremental speed protocols with a five minute warmup and when this was excluded TTE was significantly reduced (11.5 vs 10.6 min). When examining these protocols, it appears that higher starting speeds (~10 mph), shorter stage durations, and smaller speed increments allowed for more time efficient VO_{2max} performances.

Sperlich et al. (2015,24) utilized a similar speed increment of 0.31 mph, from an initial speed of 7.46 mph, with shorter stages of 30 seconds. Although this protocol was not compared to the Bruce protocol, it did not produce significantly different results from the other incremental protocols, and it had the lowest TTE observed in the study (7:18 min). The shorter stage duration of 30 seconds may not have allowed the participant to reach a plateau in VO_2 before going into a higher speed stage. The aggressive nature of the protocol may have resulted in significant anaerobic energy contributions early in the test leading to significant lactate accumulation and fatigue prior to maximal cardiovascular output. In contrast, Nordrehaug et al. (1996,17) used larger speed increments (1.24 mph) with their conservative starting speed (1.24 mph). It appears that their longer stage durations (3 min) may be the largest factor contributing to longer TTE when compared to the Bruce protocol.

It appears that protocols with higher starting speeds and moderate stage durations (1-2 min) used smaller speed increments to gradually introduce higher speeds, which ultimately led to higher TTE. It is important to note that a five minute warm was used in these protocols and removing that stage resulted in optimal TTE values (11.5 vs 10.6 min) (4). Other investigators reduced stage durations to 30 seconds to limit TTE; this modification reduced TTE below the optimal range for VO_{2max} tests (8-12 min) (24). Conversely, protocols with lower starting speeds implemented larger speed changes to reach an intensity that would elicit maximal effort while also ensuring that TTE fell within an optimal time range (7,17). However, these larger speed increments were unable to combat the low starting speeds and most often led to longer TTE than the Bruce protocol. For example, the speed increment of 0.5 mph by Duff et al. (2007,7) was too small to be used in conjunction with their conservative starting speed (2.0 mph). From these protocols, it appears that moderate stage durations (1-2 min) may be optimal for all incremental speed protocols, high and low starting speeds, because it allows the participant to reach a physiological steady state before another speed increase, while also reducing the TTE so that the protocol falls within an optimal time range.

Incremental Grade

In contrast to the previously mentioned protocols, grade may be an easily manipulated variable when attempting to achieve higher treadmill workloads. For example, some participants may find it difficult to maintain increased workloads when speed goes beyond 10 mph. Examples of treadmill protocols are available wherein speed is held constant and grade is increased; typically, these protocols start at lower initial inclines than the Bruce protocol (10%) (18,19).

The Balke protocol is a treadmill protocol that holds at 3.0 mph and increases grade from 0% by 2.5% every three minutes. Pollock et al. (1982,19) observed that the Balke protocol produced significantly lower values for VO_{2max}, VE, and RER than the Bruce protocol. Additionally, the Balke protocol had significantly higher TTE than the Bruce (25:05 vs 10:15). As before, it is likely that the conservative sustained speed (3 mph) and starting grade (0%) lead to a significantly higher TTE. After seven minutes into the Bruce protocol, the average VO_2 for all participants was roughly 30 ml/kg/min (15 ml/kg/min in the Balke). In contrast, the Balke protocol took participants 17 minutes to reach a comparable VO_2. A potential remedy to the Balke protocol could be removing the first few stages to decrease the TTE.

Pollock et al. (1976,18) also compared the Bruce and Balke protocols to the modified Astrand protocol. This protocol uses a pre-determined constant speed and begins at 2.5% grade, with a 2.5% every two minutes. The speed ranges from 5 to 8.5 mph and was set prior to the test with the goal of exhausting the participant in 7 to 10 minutes. As before, Pollock et al. (1976,18) observed that the Balke protocol produced significantly lower values for VE and RER. In contrast to their previous study, VO_{2max} was similar for both the Balke (39.4 mL $\cdot$ kg^{-1} $\cdot$ min^{-1}) and Bruce (40.0 mL $\cdot$ kg^{-1} $\cdot$ min^{-1}) protocols, however TTE was still much higher for the Balke protocol (16:53 vs 10:20 min). The Bruce protocol was able to achieve maximal physiological response in significantly less time making it a more efficient and effective protocol.

The modified Astrand protocol utilized in this study produced slightly better performances in VO_{2max} and RER, when compared to the Balke, with much lower TTE than the Bruce and Balke protocol (7:46 vs 10:20 vs 16:53 min) (18). The modified Astrand produced similar values in VO_{2max}, VE, and HR_{max} as the Bruce protocol. The only variable that was significantly different from the Bruce Protocol was RER, which was most likely a result of the less severe grade utilized in the protocol.

Furthermore, the ability to reach a VO_2 plateau as workload continues to increase was examined between protocols. The authors defined a plateau as an increase of <1 $mL \cdot kg^{-1} \cdot min^{-1}$ within one minute during a stage. It was determined that 80% of participants reached a plateau when performing the modified Astrand, but only 69% of participants achieved this metric when completing the Bruce and Balke protocols (18). These results suggest that the modified Astrand protocol may challenge the cardiovascular system to a greater degree than the Bruce and Balke protocols, while simultaneously minimizing localized fatigue that can lead to early test termination.

The authors discuss that this protocol may not be appropriate within the clinical setting because of the aggressive increases in workload. For these same reasons, the modified Astrand may be a fitting protocol for healthy individuals of higher fitness because they will be able to tolerate the rapid increases in workload as it will reduce the TTE and hopefully limit muscular fatigue of the lower extremities. It appears that incremental grade protocols need to begin with a moderate grade (2.5-5%) and maintain a moderate speed to elicit higher physiological responses in healthy populations within the optimal test duration.

Combinational Protocols

Protocols that strategically implement speed and grade changes may have more control of physiological demand on an individual. Additionally, this combinational approach may negate the difficulties of speed only and grade only protocols: maintaining higher speeds and lower extremity fatigue from steep grades. From the protocols examined in this review, only one protocol increased both speed and grade from one stage to the next like the Bruce Protocol. All other protocols manipulated only one variable when changing stage.

i. Incremental Speed and Grade

Pollock et al. (1976,18) tested the Ellestad protocol, which appears to be the most similar to the Bruce protocol. This protocol begins at 1.7 mph and 10% grade for three minutes; this is identical to the first stage of the Bruce. However, speed increases to 3 mph and increases by 1 mph every two minutes thereafter with grade remaining at 10% until it increases to 15% during the 10th minute (8). This protocol differs from the protocols to follow because speed continues to increase after a higher incline has been introduced. As a result of its similarity to the Bruce, the Ellestad protocol produced almost identical results for the following variables: VO_{2max}, VE, HR, and RER. However, TTE did not change. Unlike the Bruce protocol, the Ellestad only utilizes one grade increase of 5% when entering the 5th stage, or 10 minutes into the test. For this reason, it can be suggested that protocols utilizing more speed increments and fewer grade increments may produce comparable results as the Bruce in significantly less time.

ii. Incremental Speed, Followed by Incremental Grade

One popular combinational protocol strategy is to incrementally introduce speed up until a desired speed/pace and subsequently increase grade until volitional fatigue is reached. Miller et al. (2007,16) compared the cardiorespiratory responses of the Bruce protocol to the previously mentioned modified Astrand protocol. In contrast to the modified Astrand protocol utilized by

Pollock et al. (1976,18) where speed went unchanged, the protocol developed by Miller et al. (2007,16) was classified as a combinational protocol due to the extensive warm up that incrementally introduced speed. The protocol began with a 5-minute warmup, beginning at a pre-determined speed based on the participants' fitness level and increased 0.5 mph each minute until the selected speed was reached. Thereafter, grade was increased 2% every 2 minutes until the participant could no longer continue running. No differences in VO_{2max} were observed between the Bruce and this iteration of the modified Astrand protocol (51.3 vs 51.5 ml/kg/min), while TEE was significantly lower for the modified Astrand (12.5 vs 15.1 min). Interestingly, this modified Astrand produced higher HR_{max} values, but the Bruce protocol produced higher RER and VE values.

Sperlich et al. (2015,24) developed a Combinational protocol that incrementally increased speed every 30 seconds up to 8.95 mph, followed by a rise in grade from the initial 0% by 0.5% every 30 seconds. It was determined that their Combinational protocol did not result in differences for VO_{2max}, VE, and HR when compared to Incremental Speed and Incremental Grade protocols. The TTE was greater for the Combinational protocol (10:54), than it was for the single variable incremental protocols (7:18 and 7:30). Most importantly, the Combinational protocol produced lower RER values than the incremental grade protocol (1.18 vs 1.24) (24).

Comparably, the Combinational protocol utilized by Hamlin et al. (2012,11) began at a selected speed (4.97 or 6.21 mph), based on fitness level of the participant, with an increase in speed of 0.62 mph until a maintainable pace was achieved. Thereafter, treadmill grade was increased by 1% each minute until volitional exhaustion. When compared to the Bruce protocol, the Combinational protocol produced similar values in VO_{2max} (47.02 vs 46.81 mL · kg^{-1} · min^{-1}) with slightly lower TEE. In agreement with previous findings, RER was significantly lower and HR_{max} was significantly higher than values recorded during the Bruce protocol.

From these current findings, it appears that these Combinational protocols consistently produced lower RER values than the Bruce and Incremental Grade protocols, while Miller et al. (2007,16) observed lower VE and higher HR values as well. Higher HR maxes in conjunction with lower VE and RER values may suggest that Combinational protocols create greater cardiovascular stress with less fatigue and anaerobic energy contribution until later stages of the protocols when grade is introduced.

The above protocols reached their top speeds at 4 and 5 minutes, respectively, with incremental grade continuing for the rest of the protocol until volitional fatigue. It may be more beneficial for this transition from incremental speed to incremental grade to occur at a later time point (8 to 10 minutes). By introducing grade later in these Combinational protocols, it may allow participants to avoid lower extremity fatigue and utilization of type II muscle fibers associated with higher treadmill inclines until later in the test (7,11,16). These anaerobic energy contributions produce significant amounts of lactate leading to higher RER and VE values before aerobic energy systems can reach their maximal capabilities. A treadmill protocol that can offset fatigue until later stages and allow for greater utilization of aerobic systems may have the ability to produce significantly better results in healthy and athletic populations.

iii. Incremental Speed w/ Constant High Grade

The following treadmill protocols incrementally increased speed each stage with a consistently high grade (8-15%). These protocols were considered Combinational because in addition to the speed increments, it was believed that the significant grade throughout the entire test would create higher workloads at each stage leading to greater physiologic stress by the cessation of the test. In contrast, the purpose of the Incremental Speed protocols mentioned previously was to limit participants from overexerting themselves early in the test by limiting grade (0-1%).

Nordrehaug et al. (1991,17) compared two protocols with identical starting speeds (1.24 mph), speed increments (1.24 mph), and stage durations (3 min). The only difference between protocols being that one protocol was set at 0% grade and the other at 15%. The results revealed that VO_{2max}, RER, and VE were not significantly different from one another. However, the higher grade protocol did result in much lower TTE than the Incremental Speed protocol (11.9 vs 21.8 min) (17). These results suggest that VO_{2max} may be independent of the grade when speed and stage duration are unchanged, but the addition of a constant high grade may make the protocol more enjoyable for well-trained participants by significantly reducing the duration of the exercise test.

To this author's knowledge, there are not any other studies that use a Combinational protocol of incremental speed at a constant high grade. However, self-paced protocols commonly use a grade of 8%, while allowing the participant to determine the treadmill speed for each stage and a test endpoint of ten minutes (12,13). Hanson et al. (2016,13) instructed participants to regulate treadmill speed so that the workloads of each 2-minute stage corresponded to the following RPEs: 11, 13, 15, 17, and 20. Interestingly, the Self-Paced Treadmill protocol elicited similar VO_{2max} values to those seen from the Bruce protocol (55.6 vs 56.2 $mL \cdot kg^{-1} \cdot min^{-1}$). Additionally, the values of VE, RER, and HR_{max} for each protocol were not significantly different from one another. The Bruce protocol had a TTE of 13.28 minutes, whereas the Self-Paced protocol was time capped at ten minutes. These results allow for questions to be raised for the Incremental and Combinational Protocols. Specifically, it appears that as long as a maximal workload for a participant is achieved then VO_{2max} is not impacted by the TTE as long as it does not fall below eight minutes in duration.

Current research suggests that Combinational protocols produce similar maximal results as the Bruce protocol in a more time-efficient manner. It appears they also have a slight edge over Incremental Speed and Incremental Grade protocols as they are not reliant on a single variable to manipulate workload and intensity throughout the test. However, it is important to emphasize that speed or grade increases are not too significant from one stage to the next. The biggest limitation of the Bruce protocol is the simultaneous increase in speed and grade, especially from stage 3 to 4, which creates large increases in workload that are difficult to handle for most individuals. Therefore, to avoid the same limitation, the incremental increases in speed and/or grade need to be gradual and strategic to limit anaerobic energy contributions until the participant has reached maximal aerobic capacity.

Duration

Early investigations determined that the optimal test duration for walking/running protocols was 8 to 12 minutes in order to elicit the highest VO_{2max} values (2,15). The rationale behind this range is that test duration lasting less than eight minutes may underestimate VO_{2max} due to significant anaerobic contributions from glycolysis and lactate accumulation leading to peripheral fatigue. Additionally, shorter test durations suggest the use of high workloads, from greater speeds and/or inclines, requiring significant contributions from type II muscle fibers, which primarily rely on anaerobic sources and have higher fatigability than type I fibers (2,10).

Astorino et al. (2004,2) set out to investigate the validity of this optimal duration when young, healthy college students completed an incremental treadmill protocol. Interestingly, the optimal duration was established because the highest VO_{2max} for various incremental treadmill protocols was consistently achieved within the 8 to 12 minute range for healthy men with a mean age of 41.8 yrs (18). However, it is unclear whether this same time range would be optimal for young or athletic populations. Astorino et al. (2004,2) individualized protocols for each participant to induce fatigue and test termination at 6, 10, and 14 minutes, respectively. Treadmill speed was consistent for all trials for each participant and grade was manipulated to ensure the TTE resulted in a short (6 min), medium (10 min), and long protocol (14 min). Compared to the Long

Duration protocol (3.45 $L \cdot min^{-1}$), the Short and Medium protocols produced better performances in absolute VO_{2max} (3.56 and 3.58 $L \cdot min^{-1}$, respectively). To no surprise, the Short Duration protocol produced the highest RER values (1.19) when compared to the Medium (1.15) and Long protocols (1.13) (2).

Using participants of a similar age (mean age: 29 yrs), Kirkeberg et al. (2011,15) examined the effect of the utilizing different test durations. Short (9 min), Middle (10 min), and Long (13 min) duration protocols were achieved for each participant by manipulating speed and maintaining a grade of 3%. VO_{2max} values were not significantly different between protocol durations, however the Middle Duration (10 min) did produce the most consistent values. As before, the Long Duration (13 min) produced lower RER values (1.07 vs Middle 1.11 and Long 1.10) and slightly higher HR max values (188.8 vs Middle 187.7 and Long 186.5 bpm). These two studies incrementally increased workload by manipulating different variables. Astorino et al. (2004,2) utilized a constant speed and increased grade, whereas Kirkeberg et al. (2011,15) used a constant grade and increased speed. Interestingly, despite the differences in workload management, both studies observed minimal differences in VO_{2max} between protocols of varying durations.

i. Beyond 12 Minutes

The results from these studies suggest that protocols that continue past twelve minutes in duration produce similar or slightly lower VO_{2max} values for healthy college aged individuals. It appears that the cardiovascular systems begin to limit performance when exercise continues beyond the optimal duration.

The authors attribute lower performances in VO_{2max} to decreased stroke volume and maximal cardiac output with significant increases in body temperature (15). Longer durations lead to significant increases in body temperature resulting in peripheral vasodilation to expel the accumulate heat. This is a critical cardiovascular adjustment to ensure core temperature is properly maintained. However, diverting more blood to the periphery results in reduced venous return and end-diastolic volumes. With the heart receiving significantly less blood, stroke volume (SV) decreases and HR has to increase to maintain cardiac output (Q). This is confirmed by significantly higher HR maxes in the longer duration protocols (13 and 14 min) compared to the Short Duration protocols (6 and 9 min) (2,15). However, it appears that HR is unable to make up for the lack of SV and cardiac output is reduced as body temperature increases and exercise continues. Therefore, longer exercise durations (>12 min) appear to limit SV and Q, leading to a compromise in oxygen delivery to the working musculature and may yield the highest HR_{max} values. The optimal duration of 8 to 12 minutes to achieve maximal oxygen consumption may be highly reliant on the cardiovascular systems ability to transport oxygen blood and return deoxygenated blood back to the heart before environmental factors begin to set in and affect the efficiency of the process.

Secondly, the longer duration protocols resulted in significantly lower RER values than all other protocol durations. It has been suggested that Long Duration protocols (>12 min) allow for a more gradual increase in workload. This more conservative approach may result in less non-metabolic CO_2 production due to a reduction lactate production or enhancement in clearance. Intriguingly, Astorino et al. (2004,2) did observe the lowest values in VCO_{2max} during their Long Duration protocol. Slower increases in treadmill grade or speed will limit anaerobic energy contributions from the Glycolytic and ATP-PCr pathways. Long Duration protocols spend more time below an individual's anaerobic threshold, which allows for less accumulation of lactate, hydrogen ions (H^+), and inorganic phosphates (P_i) prior to the initiation of a workload that will elicit maximal oxygen consumption. Less accumulation ultimately means less buffering of lactate and H^+, which leads to less CO_2 being produced and a lower final RER.

ii. Under 8 Minutes

In contrast to what early research determined as the optimal duration, a Short duration protocol (6 min) did not produce lower performances in VO_{2max} than the Medium Duration. However, it is important to note that RER was significantly higher in this Short Duration protocol, suggesting greater metabolic acidosis and lactate production for protocols lasting less than eight minutes (2). It is important to point out that not only were these participants younger college students, some of the participants were runners on the cross country and track teams at the college. It is possible that shorter incremental protocols (<8 minutes) may not significantly reduce VO_{2max} performances in elite endurance-trained individuals due to their higher anaerobic thresholds and abilities to clear lactate and shuttle it to other tissues to be used as an energy substrate. For less trained individuals, the higher workloads utilized in short duration protocols would most likely result in significant lactate accumulation and greater energy contributions from anaerobic systems.

Shorter durations (<8 minutes) would be a greater challenge to anaerobic energy systems than it would be for the aerobic system. Secondly, protocols lasting longer than 12 minutes may lead to cardiovascular adjustments that can limit its ability to deliver maximal amounts of oxygen to the working musculature. From this, it appears that protocols lasting between 8 to 12 minutes allow for enough of a gradual increase in workload and allows for maximal cardiovascular efficiency. This effectively limits significant anaerobic energy production until the maximal capabilities of the aerobic system are achieved and keeps the cardiovascular system from being the limiting factor for the oxygen transport system. The optimal duration of 8 to 12 minutes appears to hold true for healthy and well-trained populations for the same reasons as it for previously investigated populations.

Conclusions and Recommendations

From current literature, it appears that the most effective treadmill protocol to elicit VO_{2max} values would be combinational in nature. These protocols rely on the manipulation of more than one variable to change workload to ultimately cause volitional fatigue. By only manipulating one variable, it may be more difficult to incrementally increase workload and reach termination of the test within the optimal duration of 8 to 12 minutes. Additionally, using a combinational protocol may eliminate the drawbacks found with maintaining higher speeds (Incremental Speed protocols) and lower extremity fatigue from higher grades

(Incremental Grade protocols). For young and athletic populations, a Combinational protocol that utilizes a moderate initial speed (5.0 mph), as well as moderate speed increments (1.0 mph) and stage durations (2 min) with the introduction of grade late in the test to elicit maximal exertion (10th min), may be optimal.

Methods

Design

This study employed a randomized, counterbalanced design. Participants were asked to complete three different graded exercise protocols (Bruce, Astrand, and Novel), each separated by a minimum of 48 and maximum 96 hours. The fourth session evaluated body composition analysis using air displacement plethysmography (BodPod, COSMED) and body circumference measurements. The duration of each lab session was approximately 20 - 30 minutes.

Participants

Fifteen participants between the ages of 18 to 28 years old volunteered to perform three graded exercise treadmill tests. Participants were recruited from the community and local university community. Participants were notified of the study by word of mouth, announcement from study personnel during classes with prior permission from the course instructor, and by announcement from study personnel during departmental faculty/staff meetings.

Prior to data collection, participants completed the American College of Sports Medicine (ACSM) Exercise Pre-participation Health Screening Questionnaire (1) and provided written informed consent. The questionnaire was used to ensure participants were: 1) meeting the threshold for planned, structured physical activity, and 2) were free of signs, symptoms, and/or known cardiovascular, metabolic, or renal disease that would prevent them from exercising to volitional exhaustion. The risks and benefits of performing a VO_{2max}

test were fully explained to each participant before giving consent. This study was approved by the Institutional Review Board for Human Subjects Research.

Procedures

i. First Trial

During the first session, participants completed the health screening questionnaire and informed consent. After consent was attained, height was measured to the nearest 0.5 centimeters using a stadiometer (Seca, Hamburg, Germany), while weight was recorded to the nearest 0.1 kilograms using a digital scale (Detecto DR 400, Webb City, MO).After body anthropometrics were recorded, participants were assigned a randomized order to perform the treadmill protocols for their three trials to avoid an order-effect bias. The Borg RPE scale and intent to perform the test to volitional exhaustion was thoroughly explained prior to the graded exercise test.

ii. VO_{2max} Trials

All VO_{2max} trials were conducted using a Trackmaster TMX425C treadmill (Full Vision, Inc., Newton, KS, USA). VO_{2max}, VE, and RER were captured by breath-by-breath assessment by a Parvomedics TrueOne® 2400 Metabolic Measurement System using open circuit spirometry (Parvo Medics, Sandy, UT, USA). Gas exchange data were analyzed using a 15 breath moving average sampling interval (20). Data were analyzed after removing any artefact from swallowing, half-breaths, or overestimations in gas exchange (26). Presence of a VO_2 plateau was determined by taking the closest 15 breath average and subtracting it from the largest 15 breath average, otherwise known as the VO_{2max}.

Based on previous recommendations (20,23,26), a VO_2 plateau was achieved if the difference between the two points described above was $\leq$ 50 mL·min^{-1} ($\Delta VO_2 \leq$ 50 mL·min^{-1} at VO_{2max}).

Participants were fitted with a nose clip and headgear, allowing them to breathe through a one-way valve (Hans Rudolph 2700 breathing valve, Kansas City, MO, USA). Prior to each trial, calibrations to the flowmeter and gas analyzer were performed according to manufacturer's standards. Participants also wore a heart rate monitor (Polar T31, 1Hz, Polar Oy, Kempele, Finland), that provided continuous monitoring due to telemetry connection to the system. Rating of perceived exertion (RPE) was assessed using the Borg 6-20 scale (5) during the last 15 seconds of each stage and immediately after participant termination. All data were collected in the Exercise Physiology lab.

The VO_{2max} attainment criteria used in this study included: 1) VO_2 Plateau: $\Delta VO_2 \leq$ 50 ml/min at VO_{2max}; 2) an $RER_{max} \geq$ 1.10; 3) HR_{max} within 10 beats/min of age-predicted maximal HR (220-age); and 4) a final RPE $\geq$ 18. Two of the four criteria had to be met for the test to be consider a VO_{2max}. Otherwise, the highest VO_2 from the maximal test was consider a VO_{2peak}. Participants were asked to continue the assigned treadmill protocol until they reached volitional exhaustion, avoiding use of the handrails, while being provided with verbal encouragement. The Borg RPE scale was displayed during the last 15 seconds of each stage and the participant was asked to point to the level of their perceived effort. All participants remained in the analysis regardless of whether they achieved a true VO_{2max} or just a VO_{2peak} for the test.

Table 1. Bruce Treadmill Protocol.

Bruce Protocol		
Stage	Speed (mph)	Grade (%)
1	1.7	10
2	2.5	12
3	3.4	14
4	4.2	16
5	5.0	18
6	5.5	20
7	6.0	22

Note: Each stage is 3 minutes in duration.

Table 2. Astrand Treadmill Protocol.

Astrand Protocol		
Stage	Speed (mph)	Grade (%)
1	5	0
2	5	2.5
3	5	5
4	5	7.5
5	5	10
6	5	12.5
7	5	15
8	5	17.5

Note: Each stage is 2 minutes in duration.

Table 3. Novel Treadmill Protocol.

Novel Protocol		
Stage	Speed (mph)	Grade (%)
1	5	1.5
2	6	1.5
3	7	1.5
4	8	1.5
5	9	1.5
6	9	10
7	9	12.5
8	9	15
9	9	17.5

Note: Each stage is 2 minutes in duration.

iii. Body Composition Trial

After completion of VO_{2max} trials, participants returned to the lab for body composition assessment via air displacement plethysmography on the BodPod™ (Cosmed USA Inc.) and circumferences using a flexible tape with attached tensiometer. Participants were asked to refrain from strenuous exercise and food at least 2 hours prior to the test, while drinking water was permitted. Participants wore form-fitting clothing, a swim cap, and removed all glasses and jewelry. Thoracic lung volume was estimated based on body weight and volume. The Siri formula was used to estimate body fat percentage from the body density results of the test. All testing and calibration procedures were performed according to manufacturer's standards.

Additional anthropometric methods included circumference measurements during the body composition lab session. Two circumference measurements of the waist and hips were recorded to assess waist-to-hip ratios (WHR) for each participant. ACSM standardized sites were used for waist and hip circumferences (1). If the two measurements for each site were not within 5 mm a third measurement was taken and the average for the two measurements was used in WHR calculations.

Statistical Analyses

All statistical analyses were performed using SPSS (version 26, IBM Corp). Dependent variables examined during analyses included VO_{2max}, VE_{max}, RER_{max}, HR_{max}, final RPE, and TTE. Dependent samples t-tests were used to explore differences between novel and criterion measures of VO_{2max}, VE_{max}, and TTE. To correct for alpha level inflation a Bonferroni correction factor was applied, so that the adjusted alpha level was 0.025.

McNemar's Test was used to assess if there was a difference in the proportion of individuals achieving previously outlined criteria between novel and criterion protocols for the following variables: VO_2 Plateau, RER_{max}, HR_{max}, and Final RPE. These continuous variables were coded into dichotomous categorical variables, yes and no, to determine whether or not maximal criteria had been reached.

Bland-Altman analyses were carried out to determine degree of bias and 95% limits of agreement between novel and criterion measures of VO_{2max}. The difference between the novel and criterion measures were plotted along the Y axis against the average of these two measures was plotted along the X axis. The mean difference and standard deviation of the differences ($SD_{difference}$) were used to define the upper and lower 95% limits of agreement (mean difference ± 1.96 * $SD_{difference}$) (9). Data are represented as mean ± standard deviation unless otherwise specified.

Results

This study examined 15 participants during maximal exercise testing on a treadmill with mean participant characteristics shown in Table 1. The three female participants and one male participant are without body composition data.

Table 4. Individual Participant Descriptive Data.

Variable	Male (*n* = 12)	Female (*n* = 3)
Age (y)	21 ± 1.76	22.67 ± 5.03
Height (cm)	177.57 ± 5.70	172.17 ± 5.51
Weight (kg)	77.48 ± 12.03	68.2 ± 8.61
Body Mass Index (BMI)	24.5 ± 3.20	23.0 ± 1.86
Waist:Hip Ratio (WHR)	0.88 ± 0.05	0.75 ± 0.04
Body Fat (%)	13.1 ± 5.50	x

Note: Values are presented as mean ± standard deviation.

Table 5. Mean values for each treadmill protocol.

Variable	Novel	Bruce	Astrand
VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)	49.40 ± 6.19	48.58 ± 6.61	49.55 ± 5.57
VE_{max} ($L \cdot min^{-1}$)	130.66 ± 20.16	129.45 ± 23.75	130.67 ± 20.57
TTE (min.sec)	9.46 ± 1.72	12.07 ± 1.62 *	11.55 ± 2.39 *

Note: Values are presented as mean ± standard deviation. * Significant ($p < 0.025$) difference from Novel.

Dependent samples t-test revealed a significant difference in TTE between Novel and Bruce ($t_{14} = 8.845$; $p \leq 0.001$). Additionally, TTE was significantly lower in the Novel protocol when compared to the and Astrand protocol ($t_{14} = 6.608$; $p \leq 0.001$). No other significant differences were revealed for VO_{2max} or VE_{max} (Table 2).

McNemar's Test revealed there were no significant differences in the proportion of individuals achieving maximal criteria between the Novel and criterion protocols (Table 3). Bland-Altman Analysis of VO_{2max} revealed that the Novel protocol exhibited a low degree of bias with tight limits of agreement when compared to the Bruce (mean bias ±95% LOA = 0.824 ± 3.163) and Astrand protocols (mean bias ±95% LOA = -0.153 ± 3.528).

Maximal Criteria			Bruce		Sig. (2-tailed)	Astrand		Sig. (2-tailed)
VO_2 Plateau ($\leq$ 50 mL·min^{-1})			No	Yes		No	Yes	
	Novel	No	2	5	.727	7	0	1.000
		Yes	3	5		1	7	
RER_{max} ($\geq$ 1.10)			No	Yes		No	Yes	
	Novel	No	1	1	1.000	2	0	.250
		Yes	0	13		3	10	
HR_{max} (± 10 bpm)			No	Yes		No	Yes	
	Novel	No	4	0	1.000	2	2	.500
		Yes	1	10		0	11	
Final RPE ($\geq$ 18)			No	Yes		No	Yes	
	Novel	No	2	2	1.000	1	3	.250
		Yes	2	9		0	11	

Table 6. Attainment of maximal criteria between novel and criterion protocols (*n* = 15).

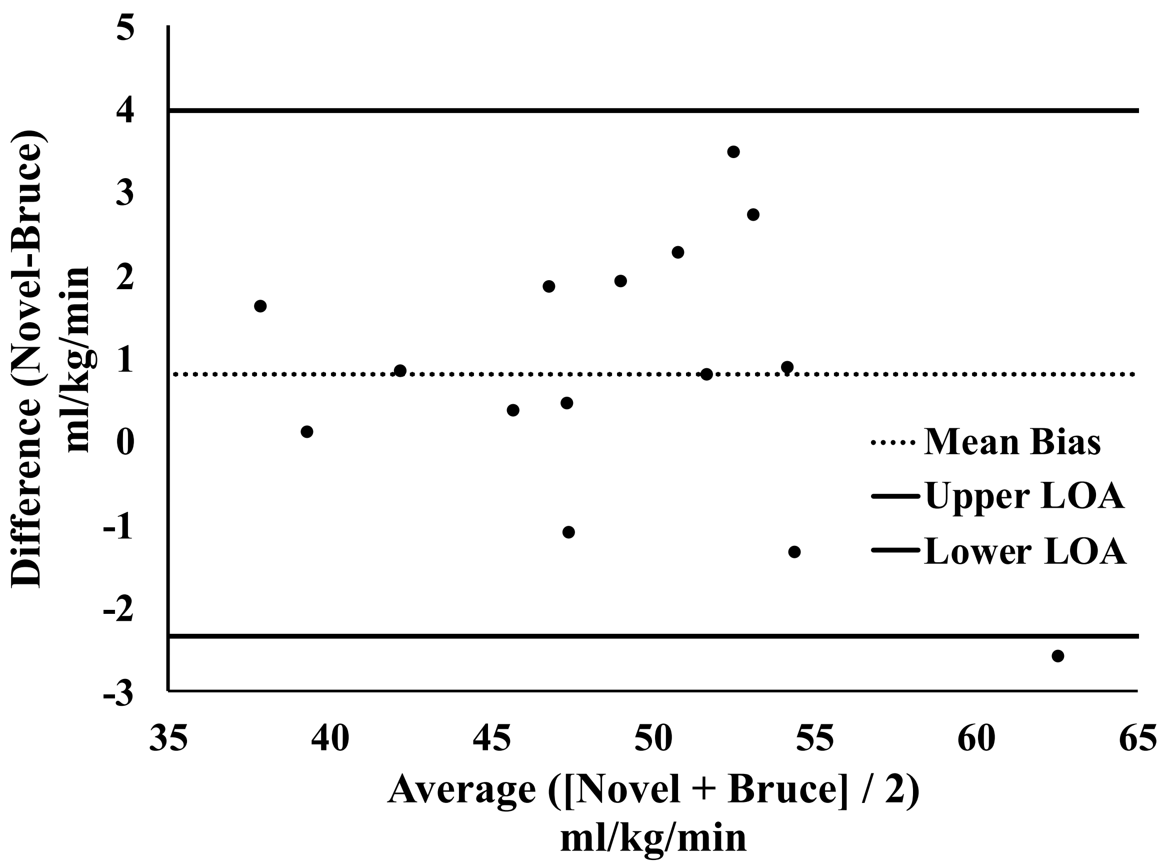

Figure 1. Agreement between Novel and Bruce protocols for VO_{2max}.

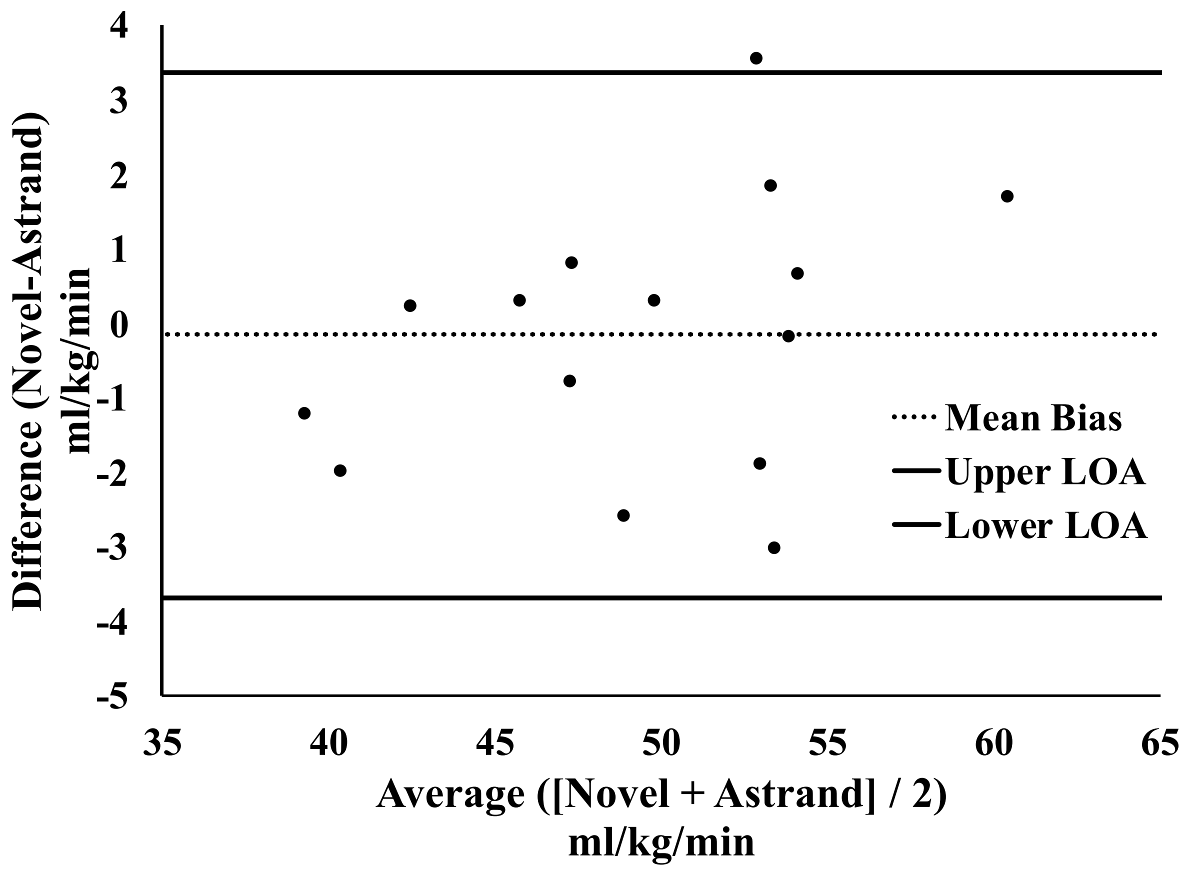

Figure 2. Agreement between Novel and Astrand protocols for VO_{2max}.

Discussion

The purpose of this study was to validate a novel VO_{2max} protocol that may be better suited for healthy or well-trained populations. To the author's knowledge, the Novel protocol used in this study is the first combinational protocol of its kind. Results indicated the Novel (49.40 ± 6.19) protocol produced a similar VO_{2max} value as the Bruce (48.58 ± 6.61) and Astrand (49.55 ± 5.57) protocols. The minimal difference in VO_{2max} when compared to the Bruce protocol has also been observed by other investigators using Incremental Speed then Grade protocols (11,16). From these results, it appears that the Novel protocol produces valid measurements of VO_{2max} when compared to criterion methods. In agreement with previous studies, it appears that VO_{2max} is independent of treadmill protocol as long as the cardiovascular system is maximally stressed and the participant does not terminate the test due to lower extremity fatigue (13). The same VO_{2max} findings suggest that the Novel protocol is an equally effective protocol to determine an individual's cardiorespiratory fitness.

The current investigation aligns with Hamlin et al. (2012,11), both resulted in VE_{max} with no difference between the Novel (130.66 ± 20.16), Bruce (129.45 ± 23.75), or Astrand (130.67 ± 20.57) protocols. In contrast, Miller et al. (2007,16) observed lower VE_{max} values from their Combinational protocol when compared to the Bruce protocol. It was suggested that the higher VE_{max} in the Bruce protocol was the result of higher grades resulting in greater localized metabolic acidosis. This produced a need for greater ventilation in order to buffer H^+ and lactate and expel CO_2 from the body. However, it is important to note that many of the participants in this study never reached the portion of the protocol where grade increase (10%) in the Novel protocol, thus exercising at the low grade (1.5%) until volitional fatigue. Therefore, the results from this study contradict the assumptions made by Miller et al. (2007,16), because VE_{max} was the same between Novel and Bruce protocols.

TTE was lower for the Novel (9:28) protocol than the Bruce (12:04) and Astrand (11:33) protocols. In contrast, the combinational protocol used by Hamlin et al. (2012,10) produced similar TTE as the Bruce protocol (10:18 vs 10:41). In this study, it appears that TTE and VO_{2max} are not dependent upon one another, meaning the Novel protocol produced valid VO_{2max} values in significantly less time. Support for the current Novel protocol being a time efficient method is provided by Kirkeberg et al. (2011,15), who evaluated different durations for treadmill protocols to volitional fatigue. It was determined that protocols of ~8, 10, and 14 minutes did not produce significantly different VO_{2max} values. Although longer duration treadmill tests produce equally valid results, this study demonstrated that a valid VO_{2max} can be obtained using a shorter duration protocol with ~10 minutes being the suggested optimal duration (15). While the Novel protocol was designed to be an incremental speed then grade, roughly half of the participants did not reach the 10 minute mark where the protocol begins to introduce incremental grade. However, not reaching the incremental grade stages had no impact on the ability of the Novel protocol to produce almost identical VO_{2max} values to that of the criterion protocols.

Self-paced protocols with a time cap at 10 minutes also provide support for more time efficient protocols. Hanson et al. (2016,13) observed a time-capped (10 min), self-paced protocol produce almost identical VO_{2max} values as the Bruce protocol (13:17 min). In addition, extending a protocol beyond 12 minutes may introduce the opportunity to underestimate VO_{2max} in moderately trained college aged participants. A previous study by Astorino et al. (2004,2) demonstrated that longer duration protocols (~ 13 min) produced significantly lower oxygen uptake values than short (~ 7 min) or moderate (~10 min) duration protocols. These authors suggest that the longer durations allow for greater increases in core temperature causing enhanced peripheral vasodilation to expel the heat. With blood shunted to the periphery, less blood volume is available centrally resulting in lower venous return and stroke volume (2). Although the longer durations of the Bruce and Astrand protocols did not significantly impact VO_{2max} performance in this study, the Novel protocol may be valuable if it can consistently produce a valid measurement in a more time efficient manner with less risk of VO_{2max} underestimation.

To confirm attainment of VO_{2max}, this study utilized a stringent VO_2 plateau criteria ($\Delta VO_2 \leq 50$ mL·min^{-1} at VO_{2max}), based on recommendations for a 15 breath moving average sampling interval (20,23,26). In the present study, the Novel protocol did not significantly impact participants' ability to achieve a VO_2 plateau when compared to the criterion protocols. Many studies still implement the most common plateau criteria of $\leq$ 150 mL·min^{-1} (or $\leq$ 2.1 mL·kg^{-1}·min^{-1}) developed by Taylor et al. (1955,25). However, it is important to understand this plateau was established from multiday, discontinuous treadmill testing. Taylor et al. (1955,25) derived this criterion by declaring that a change in VO_2 of < 50% of their protocol's stage increment VO_2 demand (4.23 mL · kg^{-1} · min^{-1}) signified a plateau. Therefore, this popular criterion may not represent a plateau in other protocols using different stage increments and smaller sampling rates (20). When using strict sampling rates, Thomson et al. (2015,26) concluded that a plateau criteria of $\leq$ 50 mL·min^{-1} produced the most accurate results for observing the presence of a VO_2 plateau. If the less strict plateau of $\leq$ 150 mL·min^{-1} had been the adopted in the current study, it would have led to an overestimation in the achievement of a VO_2 plateau (20,23). Using a strict plateau criterion allows this study to confidently assume participants who exhibited a plateau achieved their true VO_{2max} and not just a VO_{2peak}.

Attainment of secondary criteria (RER_{max}, HR_{max}, final RPE) was not significantly different following the Novel protocol when compared to the criterion protocols. Previous studies by Hamlin et al. (2012,11) and Miller et al. (2007,16) observed significant differences in RER_{max} and HR_{max} between combinational protocols and the Bruce protocol. However, it should be noted that the authors analyzed these variables on a continuous level of measure whereas the application of these cutoff measures is more so dichotomous (i.e., achieved/did not achieve). Therefore, it is possible to detect differences in raw values between each protocol while similar proportions of individuals surpassed the criterion score for a given variable. For example, the mean RER_{max} observed by Miller et al. (2007,14) for their combinational protocol (1.2 ± 0.1) and Bruce protocol (1.3 ±

0.1) eclipsed the maximal criteria used in the current study ($\geq$ 1.10). Additionally, using the mean age (23.2 ± 5.4) from the study, both the combinational and Bruce protocol achieved mean HR_{max} values that were within ±10 beats of an estimated age-predicted maximal HR for their participants (187 to 207 bpm) (Comb: 192 ± 9.9 vs Bruce: 188 ± 9.3). Lastly, final RPE was not significantly different between the protocols utilized by Miller et al. (2007,16) with both protocols achieving maximal criteria for Final RPE final ($\geq$ 18) in the current study (Comb: 18.9 ± 1.5 vs Bruce: 18.3 ± 1.1).

In conclusion, the Novel protocol used in this study can be used interchangeably with the criterion protocols to produce valid VO_{2max} performances, agreeing that VO_{2max} was independent of the protocol selected. A secondary finding was that the Novel protocol was completed in less time than the other two criterion protocols. Therefore, the Novel protocol provides practitioners with a more time efficient test that will produce valid results. All treadmill protocols were equally effective at achieving the maximal criteria for VO_2 plateau, RER_{max}, HR_{max}, and final RPE. Lastly, the obtainment of maximal criteria for RER_{max}, HR_{max}, and final RPE appears to be much more reliant on the participant rather than the selection of the Novel or criterion protocols used in this study.

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