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Concurrent Validity of a Stationary Cycling Test and the Buffalo Concussion Treadmill Test in Adults With Concussion

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Context: After concussion, a multifaceted assessment is recommended, including tests of physical exertion. The current criterion standard for exercise testing after concussion is the Buffalo Concussion Treadmill Test (BCTT); however, validated tests that use alternative exercise modalities are lacking.

Objective: To evaluate the feasibility and concurrent validity of a universal cycling test of exertion compared with the BCTT in adults who sustained a sport-related concussion.

Design: Crossover study.

Setting: University sports medicine clinic.

Patients or Other Participants: Twenty adults (age = 18–60 years) diagnosed with a sport-related concussion.

Intervention(s): Participants completed the BCTT and a cycling test of exertion in random order, approximately 48 hours apart.

Main Outcome Measure(s): The primary outcome of interest was maximum heart rate (HR_{max}; beats per minute [bpm]). Secondary outcomes of interest were the total number of symptoms endorsed on the Post-Concussion Symptom Scale, whether the participant reached volitional fatigue (*yes* or *no*), the symptom responsible for test cessation (Post-Concussion Symptom Scale), maximum rating of perceived exertion, symptom severity on a visual scale (0–10), and the time to test cessation.

Results: Of the 20 participants, 19 (10 males, 9 females) completed both tests. One participant did not return for the second test and was excluded from the analysis. No adverse events were reported. The median HR_{max} for the BCTT (171 bpm; interquartile range = 139–184 bpm) was not different from the median HR_{max} for the cycle (173 bpm; interquartile range = 160–182 bpm; $z = -0.63$; $P = .53$). For both tests, the 3 most frequently reported symptoms responsible for test cessation were headache, dizziness, and pressure in the head. Of interest, most participants (64%) reported a different symptom responsible for cessation of each test.

Conclusions: On the novel cycling test of exertion, participants achieved similar HR_{max} and test durations and, therefore, this test may be a suitable alternative to the BCTT. Future research to understand the physiological reason for the heterogeneity in symptoms responsible for test cessation is warranted.

Key Words: exercise intolerance, rehabilitation, exercise testing, mild traumatic brain injuries

Key Points

- Based on the outcome of maximum heart rate achieved at test cessation, the novel cycling test of exertion may be a suitable alternative to the Buffalo Concussion Treadmill Test.
- However, 64% of participants reported a different symptom responsible for cessation of the Buffalo Concussion Treadmill Test as opposed to the cycling test.
- Further investigation to evaluate different symptom responses leading to test cessation is warranted.

Concussions are among the most common injuries in sport and recreation. Approximately 1 in 10 Canadian youth incur a sport-related concussion (SRC) annually.[1] Sport-related concussion can be caused by an impact or force to the head, neck, or body[2] and is a heterogeneous injury resulting in a wide range of reported symptoms and clinical findings.[3] Thus, a multifaceted clinical assessment to inform diagnosis and management is recommended, which may include a neurologic scan and assessment of cognition, cervical spine function, vision, vestibular function, balance, and physical exertion.[2–4]

Current recommendations for SRC management suggest an initial period of rest (24–48 hours) followed by the gradual reintroduction of cognitive and physical activity at an intensity that does not induce or exacerbate symptoms.[2] Although most adults recover within 10 to 14 days and children in <4 weeks, an estimated 20% to 30% will experience persistent symptoms for >30 days.[4] Moreover, up to 80% of athletes who have experienced a concussion report an increase in symptoms with physical exertion.[5]

The Buffalo Concussion Treadmill Test (BCTT) is a well-established progressive and incremental modified Balke test that can be used to assess exercise tolerance.[6] When used as part of a multifaceted clinical examination for concussion, the BCTT has shown clinical utility for differentiating exercise intolerance from cervical spine and vestibulo-ocular involvement.[7,8] The BCTT can safely identify an individual's symptom-limited exercise threshold[9] and be used to guide exercise prescription after concussion.[10]

Given that the treadmill test is performed in a bipedal manner, it requires balance and coordination to remain upright. Individuals who experience dizziness and balance difficulties may have symptom increases associated with the greater sensorimotor demands from walking on a treadmill rather than from the physical exertion itself. As such, symptom exacerbation may occur because of an increased or mismatched sensorimotor stimulus rather than exertional symptoms provoked by incremental exercise. In these patients, cycling provides an alternative modality for performing exercise in a stable, seated position (ie, seated with the hands on the handlebars for support) that may better isolate the true subsymptom threshold from an exertional standpoint. Additionally, exercise testing on a stationary cycle may elicit different symptoms and levels of exercise tolerance when compared with the treadmill. Therefore, in these situations, a validated cycling test of exertion may provide a suitable alternative.

The use of the BCTT to evaluate symptom provocation with exertion has been well documented,[9–11] but no universally applicable cycling exertion protocol equivalent to the BCTT has been identified. Haider et al[12] developed the Buffalo Concussion Bike Test (BCBT), which was validated against the BCTT in adolescents with acute concussion. However, the need for advanced calculations to determine the workload required for each stage reduces its clinical utility.[12] Dematteo et al[13] used the McMaster Progressive All Out Cycling Protocol, which specified cycling resistance as a function of the participant's height,[14] in a pediatric population after concussion. Yet this protocol was not directly compared with the BCTT.

Therefore, the primary objective of our study was to evaluate the feasibility and concurrent validity of a universal cycling test of exertion compared with the BCTT in adults who sustained an SRC. The secondary objective was to describe symptoms reported on the Sport Concussion Assessment Tool 5 (SCAT5) at the time of test cessation on each modality. Lastly, we examined SCAT5 subdomain scores before and after the cycling and treadmill tests.

METHODS

Study Design and Participants

This investigation was a feasibility and concurrent validity study. We recruited a convenience sample of 20 adults (10 females, 10 males; age = 18–60 years) diagnosed with an SRC at a university sport medicine clinic to participate. This study was approved by the Conjoint Health Research Ethics Board at the University of Calgary (REB:18-0562).

Inclusion criteria were (1) adults (aged 18–60 years) with a diagnosed SRC; (2) Physical Activity Readiness Questionnaire completed by the participant indicating no contraindications to exercise testing other than SRC; (3) Physical Activity Readiness Medical Examination conducted by the treating physician, clearing the participant for maximum exercise; and (4) consent to participate. Time from concussion to assessment was recorded but not used as an inclusion or exclusion criterion. We excluded participants if (1) the concussion was sustained during a non–sport-related activity; (2) resting heart rate (HR) and blood pressure (BP) were $>$100 beats per minute (bpm) and 160/90 mm Hg, respectively; or (3) the individual scored $>$6 of 10 in symptom severity as measured on a 0- to 10-point visual Likert scale before testing.[9,12,15] Note that this scale was previously referred to as the Overall Symptom Scale,[16] and the cutoff was chosen in accordance with previous authors who used treadmill testing.[6,17]

Procedures and Instrumentation

After providing written consent, participants completed a demographic questionnaire that captured their medical, injury, and concussion history. The study team measured their height, weight, resting HR (Polar Electric), and resting BP. Before each exertional test, a registered physiotherapist or athletic therapist administered the SCAT5 using a standardized process.[18] The study team recorded the rating of perceived exertion (RPE) using the Borg scale (range = 6–20) and symptom severity as measured on a visual scale before each testing session.[9,10,12,16]

The primary outcome of interest for each exertional test was the maximum HR (HR_{max}; bpm) achieved at test cessation. Secondary outcomes were (1) total number of symptoms on the Post-Concussion Symptom Scale (PCSS), (2) volitional fatigue reached on the test (*yes* or *no*), (3) symptom responsible for test cessation (PCSS), (4) maximum RPE (Borg scale) reported at test cessation, and (5) symptom severity as measured on a visual scale from 0 to 10, and (6) time to test cessation (minutes).

The study team randomly allocated participants to complete the cycling test or the BCTT first. To maintain the allocation concealment for the order of tests administered, a random number generator was used, and a research team member who was not directly involved with the study placed the test order in sealed opaque envelopes. After consent was obtained, the tester opened the envelope to identify the first test. Participants returned to the clinic 2 days (approximately 48 hours) after the initial test to complete the second test. We chose a 48-hour duration between tests as a time period that was short enough that the participant's condition would remain stable and long enough that the first test would not affect scoring of the second test. Before beginning the second test, the tester asked the participant to rate his or her improvement from the first appointment to the second using the Global Rating of Change (GROC) scale (11-point Likert scale ranging from –5 to +5, on which –5 = *very much worse*, 0 = *unchanged*, and +5 = *completely recovered*). We used a GROC value of $\geq$2-point change to define a clinically relevant improvement or degradation in condition.[19]

During both exertional tests, the participants reported their RPE and symptom severity on a visual scale every

Table 1. Participant Demographics

Characteristic	Males (n = 10, 53%)	Descriptive Statistics No. (%)	Females (n = 9, 47%)
Previous concussions			
Yes	4 (40)		7 (78)
No	5 (50)		2 (22)
Missing	1 (10)		0 (0)
Loss of consciousness			
Yes	2 (20)		1 (11)
No	7 (70)		8 (89)
Missing	1 (10)		0 (0)
Dominant hand			
Right	10 (100)		9 (100)
Left	0 (0)		0 (0)
Missing	0 (0)		0 (0)
Diagnosed or treated for headache disorder or migraine			
Yes	0 (0)		3 (33)
No	10 (100)		6 (66)
Missing	0 (0)		0 (0)
Diagnosed with depression, anxiety, or other psychiatric disorder			
Yes	1 (10)		4 (44)
No	5 (50)		3 (33)
Missing	4 (40)		2 (22)
		Median (Interquartile Range)	
Age, y	36 (24–44)		29 (26–32)
Height, cm	182.9 (177.8–183)		168.6 (165.1–172)
Time since injury, d	38.5 (28–43)		39 (38–41)
Weight, kg	80.2 (79.4–83.9)		64.5 (64.9–74)

minute. Heart rate was continuously monitored using a wireless chest strap and recorded during the final 15 seconds of every minute of testing. Both the treadmill and cycle protocols followed the same stopping rule and continued until the participant experienced a symptom-limited threshold (defined as a ≥2-point increase from the initial symptom severity as measured on a visual scale) or reached volitional fatigue.[11,13,17,20]

The tester measured HR and BP immediately after test cessation. A trained physiotherapist or athletic therapist subsequently administered the SCAT5 after a 5-minute cooldown at a self-selected speed or workload on the testing modality. The tester recorded HR and BP for a third time after administration of the SCAT5 and monitored participants for any adverse reactions after testing. *Adverse reactions* were defined as significant abnormal responses that prevented the participant from completing the test.

Exercise Protocols

Buffalo Concussion Treadmill Protocol. We used a modified version of the BCTT previously implemented by Cordingley et al[21,22] and Morissette et al.[23] It deviates slightly from the BCTT used by Leddy et al[10] with a more conservative belt speed increment (0.2 mph/min [0.32 km/h/min] instead of 0.4 mph/min [0.64 km/h/min]) and a more conservative stopping criterion (a 2-point instead of 3-point increase in symptom severity based on a visual scale to define symptom-limited test cessation). This was done to maintain the safety of various participant populations and across multiple age groups. Under the supervision of a clinical exercise physiologist and a research assistant, the participant began by walking on a treadmill (Sport Art Fitness) at a speed of 3.2 mph [5.15 km/h] and 0% grade. The tester increased the grade by 1% per minute during the first 15 minutes, after which the speed was increased by 0.2 mph (0.32 km/h) per minute.[21]

Cycling Protocol. We used the Storer-Davis cycling protocol.[24] This protocol has been used to estimate maximum oxygen uptake in healthy sedentary and active populations aged 20 to 69 years.[24] Similar to the BCTT, the Storer-Davis protocol is a progressive, incremental ramp protocol that gradually increases the workload as the test progresses. The cycling test was performed on a cycle ergometer (Velotron Dynafit Pro; RacerMate). The test began with 4 minutes of unloaded pedaling followed by a subsequent increase in resistance of 15 W/min until test cessation. The tester instructed participants to pedal at 60 rpm. We chose the 15 W/min Storer-Davis protocol with the intention of implementing similar test durations as the BCTT on average while accounting for participants' various fitness levels, cycling experience, and physical stature. The stepwise increase in intensity mirrors the BCTT, and the simple and universal nature of the protocol facilitates straightforward administration in a clinical setting.

Statistical Analysis

We used descriptive statistics to summarize the sample characteristics. Feasibility was assessed by recording the number of participants able to complete the protocol, time to complete the protocol, adverse events, and participant attrition. We also used descriptive statistics to summarize HR, RPE, symptom severity as measured on a visual scale, and SCAT5 subscale scores before and after each exercise test. Wilcoxon signed rank tests were conducted to evaluate the differences between the primary outcome HR_{max} achieved on each of the exertional tests and the differences

Table 2. Individual Participant Outcomes by Test Type

Participant	Sport	Reached Symptom Threshold?		Symptom Responsible for Test Cessation	
		Treadmill	Cycle	Treadmill	Cycle
1	Soccer	Yes	Yes	Headache	Headache
2	Rugby	Yes	Yes	Dizziness	Dizziness
3	Cycling	Yes	No	Headache	NA
4	Snowboarding	Yes	Yes	Blurred vision	Blurred vision
5	Rock climbing	Yes	NA	Dizziness	NA
6	Motorcycle racing	Yes	Yes	Headache	Dizziness
7	Ice hockey	No	No	NA	NA
8	Squash	No	Yes	NA	Dizziness
9	Football	Yes	No	Pressure in the head	NA
10	Volleyball	Yes	Yes	Pressure in the head	Headache
11	Ultimate Frisbee	Yes	Yes	Dizziness	Pressure in the head
12	Ice hockey	Yes	No	Lightheadedness	NA
13	Ice hockey	Yes	Yes	Pressure in the head	Dizziness
14	Running	Yes	Yes	Not recorded	Pressure in the head
15	Ice hockey	Yes	Yes	Pressure in the head	Headache
16	Soccer	No	No	NA	NA
17	Climbing	Yes	Yes	Headache	Pressure in the head
18	Snowboarding	Yes	Yes	Headache	Headache
19	Cycling	Yes	Yes	Balance problems	Dizziness
20	Soccer	Yes	No	Lightheadedness	NA

Abbreviation: NA, not applicable.

in the secondary outcomes of RPE and time to test cessation. Further, we used descriptive statistics to summarize the proportion of participants who reached volitional fatigue on the cycle and treadmill tests (*yes* or *no*), the primary symptom responsible for test cessation (if test was stopped because of an increase in symptoms), and GROC scores. A Wilcoxon signed rank test was calculated to compare pretest symptom severity as measured on a visual scale to understand any change in participant status from test 1 to test 2. To adjust for multiple comparisons, we applied a Bonferroni correction with the a priori α level of .017 (ie, 0.05/3). All analyses were conducted using Stata 15 (version 15.1; StataCorp).

RESULTS

Feasibility

A total of 20 individuals consented to participate in this study. One female participant was not able to return to complete the secondary exertion test within the 48-hour period because of scheduling challenges. Thus, the final sample consisted of 19 participants who completed both tests. No adverse events were reported, and all participants were able to complete the study protocol safely. Ten participants were male and 9 were female (Table 1). Their median age was 32 years, and 11 had a history of concussion (Table 1). The median time from injury to assessment was 39 days (interquartile range [IQR] = 25–62 days; Table 1). The median GROC from test 1 to test 2 was 1 (IQR = 0–2). Further participant demographics are outlined in Tables 1 and 2.

Concurrent Validity

The pretest measures for resting HR and RPE by test type (treadmill or cycle) are summarized in Table 3. Individuals who completed the treadmill test first and then the cycling protocol reported a GROC median of 1 (range = –1 to 2). Those who completed the cycling protocol first and then the treadmill test reported a GROC median of 1 (range = –1 to 3). Pretest symptom severity on a visual scale for those who completed the treadmill test first had a median score of 1 (range = 0–4), and those who completed the cycling test first had a median score of 1 (range = 0–4). The pretest symptom severity scores measured on a visual scale between the 2 tests were not different (z = 0.949, P = .34).

The median HR_{max} was 171 bpm (IQR = 139–184 bpm) for the BCTT and 173 bpm (IQR = 160–182 bpm) for the cycling test (z = –0.63, P = .53; Table 3, Figure 1). The median test duration was not different on the BCTT (18 minutes; IQR = 11–20 minutes) and the cycling test (16 minutes; IQR = 13–24 minutes; z = –0.71; P = .48; Table 3). The maximum RPE achieved was lower on the BCTT (median = 16; IQR = 14–19) than the cycling test (median = 18; IQR = 16–20; z = –2.5; P = .013; Table 3).

Of the 19 participants who completed both tests, 12 achieved symptom-limited thresholds on both tests, 4 reached volitional fatigue on the cycle but not the treadmill,

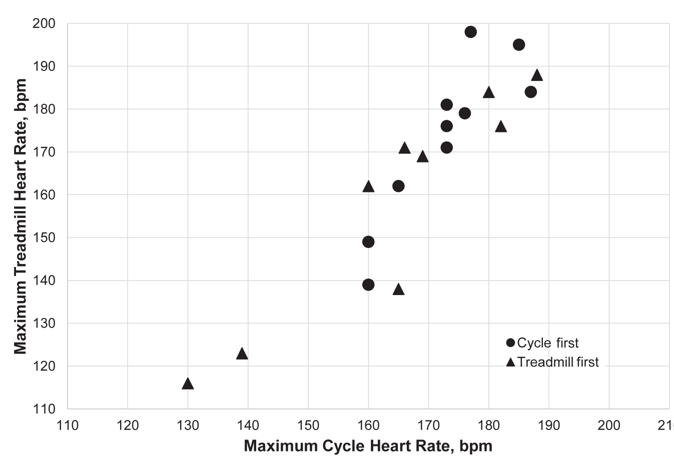

Figure 1. Maximum heart rate for the Buffalo Concussion Treadmill Test versus the cycling test of exertion. Abbreviation: bpm, beats/minute.

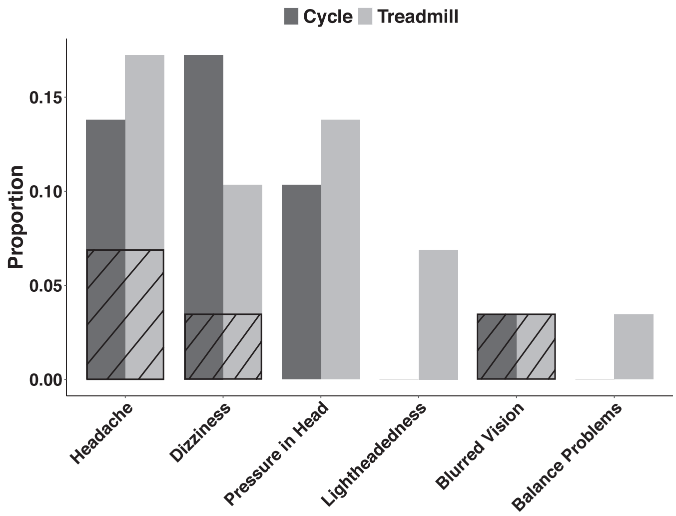

Figure 2. Symptoms responsible for test cessation. The cross-hatched sections of each symptom represent the proportion of individuals who reported that symptom as responsible for test cessation across both testing modalities.

and 1 reached volitional fatigue on the treadmill but not the cycle (Table 2). For both the BCTT and the cycling test, the 3 most frequently reported symptoms responsible for test cessation were headache, dizziness, and pressure in the head (Figure 2). Of interest, among the participants who achieved symptom-limited thresholds on both tests, 7 of 11 (64%) had a different symptom responsible for test cessation and 4 of 11 (36%) reported the same symptom responsible for test cessation on both tests (Table 2).

The SCAT5 Subdomain Scores

The descriptive statistics for the SCAT5 before and after each of the exertion tests are supplied in Table 4; 18 individuals were included in the SCAT5 subdomain analysis. The participants who were missing SCAT5 data (n = 2) were excluded.

DISCUSSION

We assessed the concurrent validity and feasibility of a universal cycling test of exertion compared with the commonly used BCTT and described symptoms related to symptom-limited test cessation.[12] Maximum HR achieved and time to test cessation were not different between the BCTT and the cycling test of exertion. Although the exertional tests appeared to be similar when evaluating conventional exercise testing variables (ie, HR_{max} and test duration), the symptoms responsible for test cessation were heterogeneous. This may suggest different physiological responses to each test and, as such, may have implications for the interpretation and comparison of results between modalities. Of interest, the maximal RPE reported during the cycling test was greater than that achieved on the treadmill test, indicative of a higher level of perceived exertion during the former. Finally, SCAT5 subdomain scores appeared similar at pre-exertion and postexertion with both modalities.

Comparison With Previous Literature

We used a cycling protocol that was universal and not customized to individual participants. In contrast, Haider et al[12] implemented an individually tailored cycling protocol by estimating oxygen consumption at each stage of the BCTT and providing an equivalent cycling power output based on each participant's body mass. In the only study we know of to compare individuals' responses during a cycling test (BCBT) with the BCTT, Haider et al[12] examined the difference in concussion symptom responses between the BCTT and the BCBT in 20 adolescents (mean age = 15.9 ± 1.1 years) after concussion (<10 days). Similar to our results, Haider et al[12] found that HR_{max} was equivalent between the tests; however, they did not randomize the order of the tests (ie, the BCTT was always performed first). Also, Haider et al[12] did not examine symptoms after test cessation. These findings suggest that both the cycling protocol presented in our study and that in the work of Haider et al[12] may be suitable alternatives to the BCTT. However, the lack of agreement between symptoms responsible for test cessation in the current study (Table 2) illustrates that equivalent HR_{max} values may not always indicate an equivalent physiological response, which should be considered when using alternative testing modalities.

Across both testing modalities, the most frequent symptoms responsible for test cessation were headache, dizziness, and pressure in the head; yet for most participants (64%), a different symptom limited their exercise on the treadmill compared with the cycle (Table 2). The differences between symptoms responsible for test cessation on different exercise modalities may be attributable to the various biomechanical and physiological responses required for each test. For example, exercise on a treadmill is performed in a bipedal upright position, which requires more dynamic balance and stabilization than cycling.[25] The treadmill requires greater integration of vestibular, visual, and somatosensory input to maintain balance, which may increase symptoms.[25] Cycling, on the other hand, occurs in a seated position and does not require the same degree of sensory and motor integration. In addition, the vertical up-and-down motion of the head when moving from step to step on the treadmill increases the otolithic input from the peripheral vestibular system.[25] This

Table 3. Pretest and Immediate Posttest Physiological Values With Corresponding Wilcoxon Signed Rank Tests

	Median Value (Interquartile Range)				
	Resting		Maximum		
Variable	Pretreadmill	Precycle	Posttreadmill	Postcycle	*z* Score (*P* Value)
Heart rate, beats/min	75 (69–89)	82.5 (70–91)	171 (139–184)	173 (160–182)	0.63 (.53)
Rating of perceived exertion	6 (6–6)	6 (6–7)	16 (14–19)	18 (16–20)	−2.5 (.013)
Test duration, min	NA	NA	18 (11–20)	16 (13–24)	−0.71 (.48)

Abbreviation: NA, not applicable.

Table 4. Sport Concussion Assessment Tool 5 Scores Before and After Each Test of Exertion

	Median (Interquartile Range)							
	Buffalo Concussion Treadmill Test				Cycle			
	Pre		Post		Pre		Post	
Score	Symptom Threshold	Volitional Fatigue[a]	Symptom Threshold	Volitional Fatigue[a]	Symptom Threshold	Volitional Fatigue[a]	Symptom Threshold	Volitional Fatigue[a]
Total No. of symptoms (of 22)	7.5 (0–17)	2.5 (2–3)	9 (0–21)	1.5 (1–2)	5 (0–20)	2 (2–2)	7.5 (2–22)	4 (0–8)
Symptom severity (of 132)	9 (0–45)	2.5 (2–3)	9.5 (0–53)	1.5 (1–2)	6 (0–48)	2.5 (2–3)	10 (2–49)	5.5 (0–11)
Immediate memory (of 15)	15 (15–15)	15 (15–15)	15 (12–15)	15 (15–15)	15 (13–15)	15 (15–15)	15 (11–15)	15 (15–15)
Concentration score (of 5)	5 (3–5)	4.5 (4–5)	5 (2–5)	4 (4–4)	4 (2–5)	5 (5–5)	5 (3–5)	3.5 (2–5)
Balance Error Scoring System total (of 30)	4 (0–9)	1.5 (1–2)	4 (1–10)	0.5 (0–1)	4.5 (0–11)	5 (4–6)	6.5 (0–10)	4.5 (2–7)
Delayed recall (of 5)	3 (1–5)	4.5 (4–5)	4 (0–5)	1 (0–2)	5 (3–5)	3.5 (3–4)	4 (1–5)	2.5 (2–3)

[a] Both tests (n = 2).

differs from the stimulus on the cycle, as the head does not move to the same degree as expected on the treadmill.

Lastly, as mentioned, of the 19 participants who completed both tests, 12 (63%) reached symptom thresholds on both tests and 2 (11%) reached volitional fatigue on both tests (Table 2). Of the individuals who reached volitional fatigue on 1 test, 4 participants (80%) reached volitional fatigue only on the cycle, and 1 (20%) reached volitional fatigue only on the treadmill. Individuals who are untrained on a cycling ergometer may elicit a lower HR_{max} and maximum oxygen uptake than with a treadmill.[26] However, similar HR_{max} values were collected during exertion testing on both the treadmill and the cycle, which suggests that a lack of training on the cycle was likely not responsible for reaching volitional fatigue on the cycle but not the treadmill (Table 2). Taken together, we hypothesized that these individuals may have experienced an exacerbation of symptoms secondary to locomotion on a treadmill and not physical exertion.

The data summarized in Table 4 describe SCAT5 subdomain scores before and after exercise testing. Hänninen et al[27] studied professional Finnish hockey players and suggested that SCAT subdomain scores may be classified into a set of ranges: broadly normal, below or above average, unusually low or unusually high, and extremely low or extremely high. With these classifications in mind, the data in Table 4 demonstrate that all subdomain scores except 1 remained in the same classification from pretest to posttest across both the treadmill and the cycle in those who reached a symptom-limited threshold. The only subdomain that changed classifications was the modified Balance Error Scoring System score from precycle to postcycle. Nonetheless, a 2-point change from a median 4.5 of 30 to 6.5 of 30 is considered to be within the range of normal variation.[27] Lastly, the increase in symptoms responsible for test cessation in 17 of 19 individuals who reached symptom thresholds on at least 1 test is not reflected in the total number of symptoms or the symptom severity scores. Thus, the total number of symptoms and symptom severity scores on the SCAT5 alone may not adequately quantify the nature and intensity of symptoms. The addition of symptom severity as measured on a visual scale and specific symptom reports at the time of test cessation may assist the clinician in further assessment and management.

Potential Mechanisms for Exercise Intolerance

As stated, the most frequent primary symptoms responsible for test cessation were headache, dizziness, and pressure in the head; this was the same between exertion modalities (Table 2). Exercise intolerance is not experienced by every individual who experiences SRC. However, the literature[28,29] suggested that exercise intolerance after SRC may be explained by an altered vagal tone and possibly impaired autoregulatory ability of the cerebral vasculature. Specifically, Clausen et al[28] observed this dysregulation in female collegiate athletes with postconcussion syndrome (>6-week recovery), who appeared to have an attenuated cerebrovascular reactivity response. Yet, we captured no cardiovascular or cerebrovascular metrics in our investigation. Future research is warranted to delineate the physiological changes and differential symptom responses during and after exertion with both the cycle and treadmill exertional testing protocols.

Implications for Future Exercise Testing After SRC

In this study and previous studies,[9,12] HR_{max} was the primary outcome, as it is the measure by which exercise is prescribed to individuals after a concussion. Still, HR_{max} is only 1 measure of exertion and, thus, other novel measures of exertion may better reflect an individual's physiological response to exertional testing.[30] For example, in uninjured participants, using proportions of HR_{max} to prescribe exercise (ie, exercise at a percentage of HR_{max}) did not accurately reflect metabolic demand.[30] We demonstrated similar HR_{max} values on both tests, but individuals experienced different symptoms responsible for test cessation. Given this, other, more subtle differences in how participants respond to each modality of exercise may not be reflected in HR_{max}. Thus, HR_{max} may not provide an accurate representation of an individual's physiological response to incremental exercise. Going forward, it may be prudent to consider other physiological factors such as oxygen uptake, $\dot{V}CO_2$, lactate threshold, and cerebral blood flow, velocity, and oxygenation while remaining cognizant of postural influences on cardiovascular and cerebrovascular metrics. Additionally, because alterations in the function of the cervical spine system, the vestibulo-ocular system, and the sensorimotor system more broadly have been observed after concussion,[31] it could be that the heterogeneity in symptoms occurs secondary to various sensory and motor alterations. As each modality of exercise offers unique and distinct stimuli, it is possible that the differences in symptoms can be attributed to the different sensorimotor stimuli. In any case, a more comprehensive approach may provide better insight in this respect.[32]

From a clinical standpoint, the cycling protocol used in this study has practical advantages. As the protocol remains the same for every individual, it is straightforward and simple to administer. Therefore, the universal nature of the protocol requires less administration time, reduces the burden on clinical care, and provides an alternative to treadmill testing in settings where a treadmill is not available.

Limitations

Although most test protocols were standardized and the time between the tests was as close to 48 hours as possible, recovery may have occurred during this time. To control for this, we measured GROC at the time of the second test, when 25% of participants had experienced a clinically relevant improvement in symptoms (defined as $\geq$2 points improvement between tests).[19] To minimize the effect of order on the outcome of interest and reduce the likelihood that recovery between testing sessions would confound the outcome measures, we randomized the test order. Furthermore, for individuals who reported a clinically relevant recovery (as per the GROC scale) between test times, 3 reached symptom thresholds on both tests, 1 reached symptom threshold on the treadmill but not the cycle, and 1 reached symptom threshold on the cycle but not the treadmill. Thus, the reported clinically relevant improvement did not appear to be an important factor between test times. The resistance increment for the cycling test was maintained at 15 W/min for all participants per the Storer-Davis protocol.[24] Although this straightforward resistance promotes ease of administration of this protocol, it is possible that the resistance may be too great for individuals who have a relatively low muscle mass or too little for individuals who are well trained or have a greater muscle mass. As such, the test length may be too short or too long, respectively. Although test durations did not differ significantly, it may be beneficial to alter the incremental resistance based on participant weight and muscle mass to optimize test duration. Also, the physicians referred to the study only those patients who had symptoms exacerbated by physical activity and whom they deemed suitable for exercise testing. Hence, a selection bias may have existed: the individuals who were referred to the study may have been more likely to report symptoms with exertion testing. However, we would not expect that the nature of this selection bias would affect the relationship between the test outcomes. Moreover, our sample may have overrepresented what is typically seen in a representative sample of individuals who have experienced SRC. Because we conducted intraindividual comparisons with respect to the variables of interest, individual confounding factors (eg, level of fitness, primary sport, initial severity of symptoms) were controlled for and were not expected to affect the study outcomes. This study included a subsample of patients referred from a university sport medicine clinic, so these results may not be generalizable to all ages and all individuals who have experienced SRC. Lastly, as this was a pilot study, a convenience sample of 20 participants was recruited. Thus, there is potential for type II error. Yet the IQRs for HR_{max} and test duration overlapped and the point estimates appeared similar. These findings can be used to inform future studies designed to build on this work and evaluate the protocol with an appropriately powered sample.

CONCLUSIONS

In summary, HR_{max} did not differ between the cycling test and the BCTT. For both modalities, the 3 most frequent primary symptoms responsible for test cessation were headache, dizziness, and pressure in the head. However, participants reported different symptoms as the reason for test cessation on the cycle compared with the treadmill. This highlights certain implications when comparing and interpreting the results from each of these tests and the possible confounding factors that may be related to symptom onset. The cycling test of exertion seemed to be a suitable alternative to the BCTT in adults who had experienced SRC. Future research to evaluate the underlying mechanisms driving differential symptom responses to exertion is warranted.

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