

Performance on the Balance Error Scoring System Decreases after Fatigue

By: Joseph C Wilkins, Tamara C Valovich McLeod, David H Perrin, and Bruce M Gansneder.

Wilkins, J., Valovich McLeod, T.C., [Perrin, D.H.](#), Gansneder, B. (2004). Performance on the balance error scoring system decreases after fatigue. Journal of Athletic Training, 39:156-161.

Made available courtesy of NATIONAL ATHLETIC TRAINERS ASSOCIATION:
<http://www.nata.org/jat/>

*****Note: Figures may be missing from this format of the document**

Abstract:

Objective: To determine the immediate effects of a whole-body fatigue protocol on performance of the Balance Error Scoring System (BESS), a postural-stability test commonly used as part of a concussion-assessment battery.

Design and Setting: Subjects were assigned to a fatigue or control group and were assessed before and immediately after a 20-minute fatigue protocol or rest period.

Subjects: Fourteen fatigue subjects and 13 control subjects participated in this study. All subjects were male and free of vestibular disorders, and none had suffered a mild head injury or lower extremity injury in the preceding 6 months, as described through self-report.

Measurements: We measured performance on the BESS for 9 stance-surface conditions and summed each condition to obtain a total score. Using the Borg scale, we also measured ratings of perceived exertion before, during, and after the fatigue protocol or rest period.

Results: We found a significant increase in total errors from pretest to posttest in the fatigue group (14.36 ± 4.73 versus 16.93 ± 4.32), a significant decrease in errors in the control group (13.32 ± 3.77 versus 11.08 ± 3.88), and a significant difference between groups on the posttest. The rating of perceived exertion scores were significantly different between the fatigue and control groups at the middle (13.29 ± 1.59 versus 6.23 ± 0.83) and end (15.86 ± 2.38 versus 6.15 ± 0.55) of the fatigue or rest period.

Conclusions: The BESS error scores increased immediately after the fatigue protocol, demonstrating that balance ability diminished. Clinicians who use the BESS as part of their sideline assessment for concussion should not administer the test immediately after a concussion due to the effects of fatigue.

Key Words: balance, exertion, concussion, injury assessment

Article:

Sports medicine clinicians often use balance assessments in the evaluation and rehabilitation of a variety of postural-stability problems related to orthopaedic and mild head injuries. A variety of methods have been developed to assess postural stability both subjectively and objectively in athletes, including the Romberg test,^{1,2} the Chattecx Balance System (Chattanooga Group, Inc, Chattanooga, TN), the EquiTest system (NeuroCom International, Inc, Clackamas, OR),²⁻⁷ the Biodex Stability System (Biodex Medical Systems, Shirley, NY),⁸ and more recently, the Balance Error Scoring System (BESS).^{6,7,9,10}

The BESS is a clinical field test that can be used for sideline evaluations of an athlete's postural stability after a mild head injury (MHI).^{7,9} It was developed to provide health care professionals with an inexpensive and objective way to assess postural stability outside the laboratory. The BESS measures an athlete's postural stability through a clinical-assessment battery and is scored by counting the errors the athlete commits during the tests.⁶ The BESS can be used to compare baseline scores with scores after an MHI. Advantages of the BESS are that it can be used for sideline application, is less expensive than force-platform systems, and requires less training for effective administration.⁶

The BESS is a valid and reliable method of measuring postural stability.^{6,7} Error scores were significantly correlated with those on the EquiTest long forceplate and ranged from 0.30 to 0.78.⁶ Good test-retest reliability ($r = .673$) of the BESS has also been reported.¹¹ The BESS scores were similar to the Sensory Organization Test composite scores in athletes with MHIs. Low scores on the Sensory Organization Test paralleled high error scores found with the BESS. Thus, the BESS is sensitive to acute postural-stability abnormalities after MHI.⁷ Additionally, high intraclass correlation coefficients for both intertester (.78 to .96)⁶ and intratester (.87 to .98)¹¹ reliability were noted in scoring BESS errors.

Postural stability decreases acutely after isolated muscle fatigue¹²⁻¹⁴ and whole-body (central) fatigue.¹⁵⁻²⁰ However, these investigators measured postural stability using force-platform systems. Only one group has studied the effect of fatigue on the performance of the BESS. Crowell et al²¹ demonstrated decreased postural stability after a fatigue protocol consisting of squat jumps, sprints, and treadmill running in male and female club-sport athletes. To our knowledge, the immediate effects of fatigue on BESS performance have yet to be studied in a population of National Collegiate Athletic Association Division I athletes. Therefore, our purpose was to determine the acute effects of a whole-body fatigue protocol on performance of the BESS.

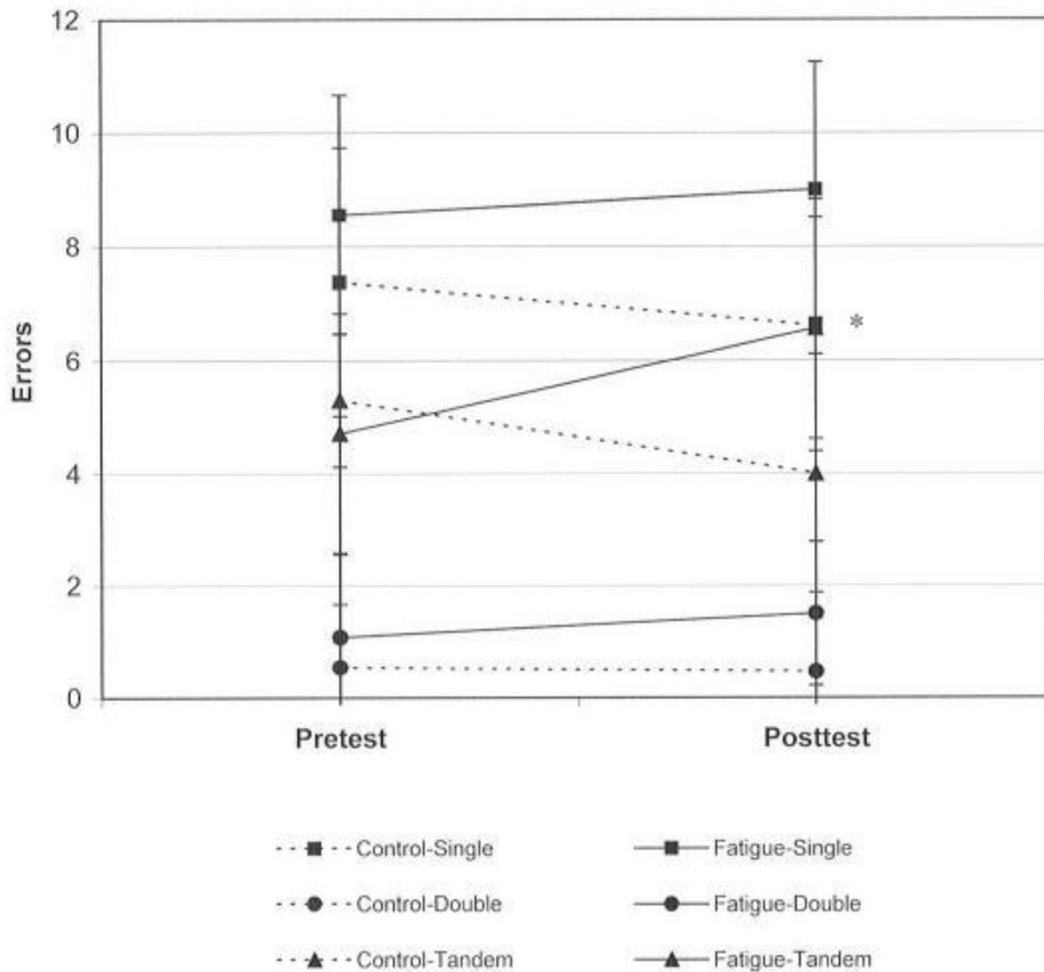


Figure 1. Time × stance × group interaction. Each stance represents the combination of all 3 surfaces. *Significantly more errors than control group at posttest for the tandem stance.

METHODS

Subjects

Twenty-seven male Division I college athletes (age = 20.3 ± 1.46 years, height = 180.15 ± 7.54 cm, mass = 81.68 ± 8.48 kg) were tested twice during 1 session. Any subject who had suffered a musculoskeletal injury to a lower extremity or a head injury in the 6 months before testing was excluded from the study. We screened subjects for any preexisting visual, vestibular, or balance disorders through self-report. Subjects were randomly assigned to 1 of the 2 test groups, control or fatigue. All subjects read and signed the informed consent form approved by the institutional review board, which also approved the study procedures.

Procedures

Balance Error Scoring System. Postural stability was measured using BESS error scores. The BESS comprises 9 conditions: double-leg, single-leg, and tandem stances on firm, foam, and

tremor box surfaces. The firm surface was the floor of a collegiate gymnasium. The foam surface consisted of a 46 × 46 × 13-cm block of medium-density foam (Exertools, Inc, Santa Clara, CA). The tremor-box conditions were performed on the Teton Tremor Box (Exertools, Inc). A stopwatch was used to time each of the 20-second trials. Previous investigations have demonstrated good intertester (.78 to .96)⁶ and intratester reliability (.87 to .98).¹¹ One BESS error was scored if the subject engaged in any of the following: (1) lifting the hands off the iliac crests; (2) opening the eyes; (3) stepping, stumbling, or falling; (4) moving the hip into more than 30° of flexion or abduction; (5) lifting the forefoot or heel; or (6) remaining out of the test position for longer than 5 seconds. Error scores were calculated for each of the 9 conditions and summed to obtain the total BESS score. A full description of BESS scoring and reliability has been previously published.⁶

Before the pretest, subjects were allowed to familiarize themselves with the different conditions. They were first allowed to try standing on the firm and tremor surfaces. Once they were comfortable standing on each surface, we then instructed them in the correct positioning for each of the 9 conditions. The double-leg stance conditions consisted of the subject standing with feet together. The single-leg stance was performed on the nondominant leg, as determined by which limb the subject would not preferentially use to kick a ball. The dominant leg was positioned so that the hip was flexed to approximately 30° and the knee flexed to 90°, leaving the foot approximately 6 to 8 in (15.24 to 20.32 cm) off the ground. We instructed the subject not to lean the dominant leg on the nondominant leg. The nondominant foot was positioned behind the dominant foot in the tandem stance, and the subject was instructed to maintain the stance with the great toe of the nondominant foot touching the heel of the dominant foot. For all conditions, we instructed the subject to remain still with eyes closed and hands on the hips. After the instruction, each subject was given 2 familiarisation trials on each condition before the actual data collection. Previous researchers have demonstrated a practice effect in which scores on the third day were significantly lower than the initial attempt.²² During the familiarisation and testing sessions, each condition lasted 20 seconds, and at no point was the clock stopped. We instructed the subject to remain as still as possible; if he moved from the test position, he was to return to it as soon as possible. During the testing, the scorer (J.C.W.) was positioned 8 to 10 ft (2.44 to 3.05 m) away from the subject, so the subject's eyes, hands, and feet could all be observed. An analysis of intertester reliability between the scorer and an experienced investigator whose intratester reliability has already been established¹¹ demonstrated good intertester reliability of .90 (intraclass correlation coefficient [2, 1]). The order of BESS testing was counterbalanced across the 9 conditions for each subject. Our counterbalancing scheme consisted of 3 sets of 9 subjects. In a set, each subject started with a different condition first, so the effects of exertion would not be greater for one condition than another. The same order of testing was used for each subject's pretest and posttest.

Ratings of Perceived Exertion. We used a 15-point Borg scale (6-20)²³ to measure ratings of perceived exertion (RPE) in an attempt to quantify the amount of exertion displayed by each subject before, midway through, and after the exertion protocol. The 15-point Borg scale has been recommended for applied investigations of perceived exertion and for predictions of exercise intensity during sports and rehabilitation.²⁴

Fatigue Protocol. Participants performed the fatigue protocol with running shoes, but all BESS testing was performed without shoes. After the familiarization period, all subjects underwent a pretest in which they performed each of the 9 conditions. Subjects in the control group then rested for 20 minutes before undergoing a posttest, whereas subjects assigned to the fatigue group performed the fatigue protocol, which was immediately followed by the posttest. The fatigue protocol was a circuit design using the space on and around a regulation-sized basketball court. The protocol consisted of 7 stations. Stations 1 and 7 were moderate jogging stations, around the gym, of 5 and 2 minutes, respectively. Stations 2 and 6 were both 3 minutes of straight-line sprint work. Stations 3, 4, and 5 consisted of 2 minutes of push-ups, 2 minutes of sit-ups, and 3 minutes of 12-in (30.48-cm) step-ups, respectively. Participants were instructed to do as many sit-ups and push-ups as they could in the designated amount of time.

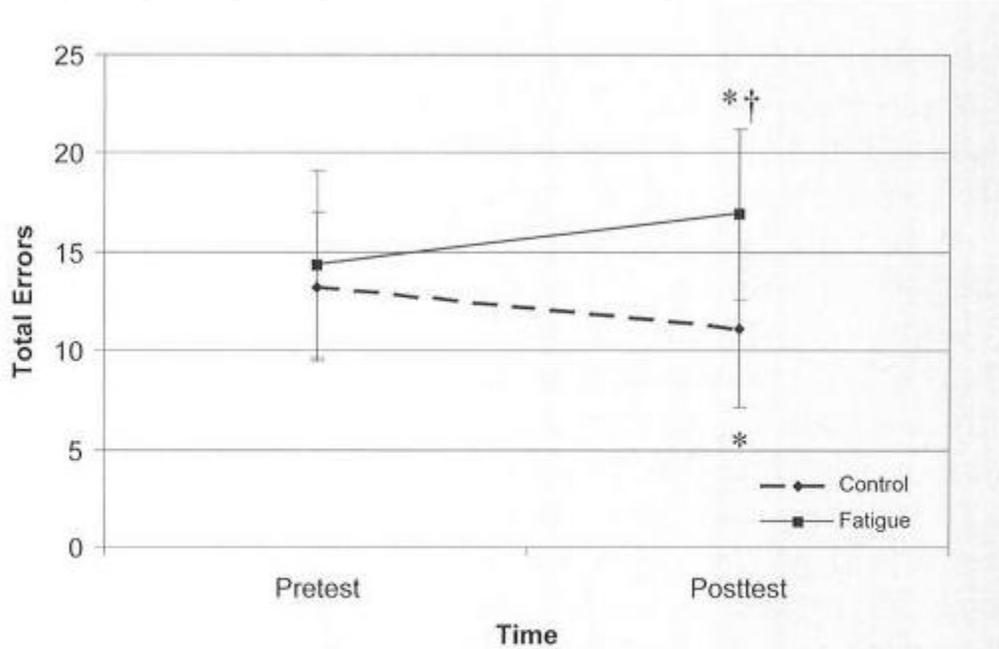


Figure 2. Balance Error Scoring System (BESS) performance before and after the fatigue or rest period. The score represents the summed error score of the 9 conditions. *Significantly different from pretest. †Significantly different from control group.

Ratings of Perceived Exertion at the Beginning, Middle, and End of the Fatigue Protocol or Rest Period

| | Control (n = 13) | | | Fatigue (n = 14) | | |
|---------|------------------|--------|------|------------------|--------|-------|
| | Beginning | Middle | End | Beginning | Middle | End |
| Range | 3 | 3 | 2 | 5 | 5 | 7 |
| Minimum | 6 | 6 | 6 | 6 | 11 | 12 |
| Maximum | 9 | 9 | 8 | 11 | 16 | 19 |
| Mean | 6.92 | 6.23 | 6.15 | 7.21 | 13.29 | 15.86 |
| SD | 1.04 | 0.83 | 0.55 | 1.58 | 1.59 | 2.38 |

Statistical Analysis

Using SPSS software (version 10.0; SPSS Inc, Chicago, IL), we computed a repeated-measures analysis of variance with 1 between-subjects factor (group) and 3 within-subjects factors (time, surface, stance) to investigate the effects of fatigue on BESS performance. A separate repeated-measures analysis of variance with 1 between-subjects factor (group) and 1 within-subjects factor (time) was used to evaluate RPE. We employed simple main-effects testing with 1 between-subjects factor (group) and 1 within-subjects factor (time) to locate the specific group differences for each stance on the interaction and the Tukey honestly significant difference post hoc analysis to locate pairwise differences for any significant main effects. We set our alpha level a priori at .05.

RESULTS

Our findings did not reveal a significant 4-way interaction for the effects of fatigue on BESS performance ($F_{4,100}^2 = 2.197, P = .075$). We did show a significant 3-way interaction for time \times stance \times group (Figure 1) ($F_{2,50}^3 = 3.795, P = .029$) and significant 2-way interactions for time \times group (Figure 2) ($F_{1,25}^2 = 23.979, P < .0001$), time \times surface ($F_{2,50}^2 = 3.935, P = .026$), and surface \times stance ($F_{4,100}^2 = 6.211, P < .0001$).

Simple main-effects testing for each stance of the 3-way group \times time \times stance interaction revealed that the effects of fatigue were more pronounced during the tandem-stance conditions. For the tandem stance, we found a significant time \times group interaction ($F_{1,25}^2 = 16.47, P < .001$). Post hoc analysis of this interaction demonstrated that the fatigue group had scored significantly more errors than the control group during the posttest (6.6 versus 4.0 errors). The main-effects testing for the single-leg stance did not result in a significant time \times group interaction ($F_{1,25}^2 = 3.032, P = .094$); however, there was a main effect for group ($F_{1,25}^2 = 5.125, P = .033$), with the fatigue group scoring more errors than the control group. We had neither significant main effects nor a 2-way interaction with the double-leg condition ($F_{1,25}^2 = 1.017, P = .323$).

Post hoc analysis of the time \times surface interaction revealed no significant differences between the pretest and posttest scores for each of the surfaces; yet at the pretest, subjects scored significantly more errors on the foam than the firm surface (2.36 versus 0.80 errors), whereas at

the posttest, subjects scored significantly more errors on the foam surface compared with the firm and tremor surfaces (2.61 versus 0.95 versus 1.13 errors). Further investigation of the 2-way surface \times stance interaction demonstrated that on the firm surface, subjects scored more errors in the single-leg stance than in the double-leg or tandem stances, that all 3 stances differed from one another on the foam surface, and that subjects scored significantly fewer errors in the double-leg stance than in the single-leg or tandem stance while on the tremor surface.

The descriptive statistics for our RPE analysis are presented in the Table. Our analysis of the RPE scores revealed a significant main effect for time ($F^{sub 2,50} = 91.172$, $P = .0001$) and group ($F^{sub 1,25} = 157.013$, $P = .0001$) and a significant time \times group interaction ($F^{sub 2,50} = 158.800$, $P = .0001$) for the RPE results. Post hoc analysis indicated the RPE scores for the fatigue group increased from beginning to middle to end of the fatigue protocol (7.21 ± 1.58 versus 13.29 ± 1.59 versus 15.86 ± 2.38), whereas the control group's scores did not change (6.92 ± 1.04 versus 6.23 ± 0.83 versus 6.15 ± 0.55). The RPE scores were significantly different between the fatigue and control groups at the middle (15.86 ± 2.38 versus 6.15 ± 0.55) and end (13.29 ± 1.59 versus 6.23 ± 0.83) of the fatigue or rest period (Figure 3), with the fatigue group demonstrating increased RPE scores at both time points. No differences between groups were found in the RPE score taken at the beginning of the fatigue or rest period.

DISCUSSION

Our main findings were that the fatigue group scored significantly more total errors on the posttest than on the pretest and significantly more errors than the control group at the posttest. In addition, fatigue affected performance on the tandem conditions more than on the double-leg or single-leg conditions. Our overall findings demonstrate a decrease in postural stability as a result of fatigue as measured by the BESS total error score. We will discuss our findings within the context of fatigue and postural stability, the potential mechanisms behind the effect of fatigue on balance, and the clinical application of these findings on the BESS as a concussion-assessment tool.

A decrease in postural stability after fatigue has been found in previous studies using both central 16-19,21,25,26 and local means of fatigue.13,27-30 Our protocol was chosen to replicate the fatigue athletes would experience during the course of a game or practice. We feel confident that the changes in RPE scores demonstrate that our subjects were fatigued to a level representative of working at 80% of maximal heart rate or maximal oxygen uptake ($\dot{V}O_2^{max}$) and that this fatigue elicited postural instability during the posttest.

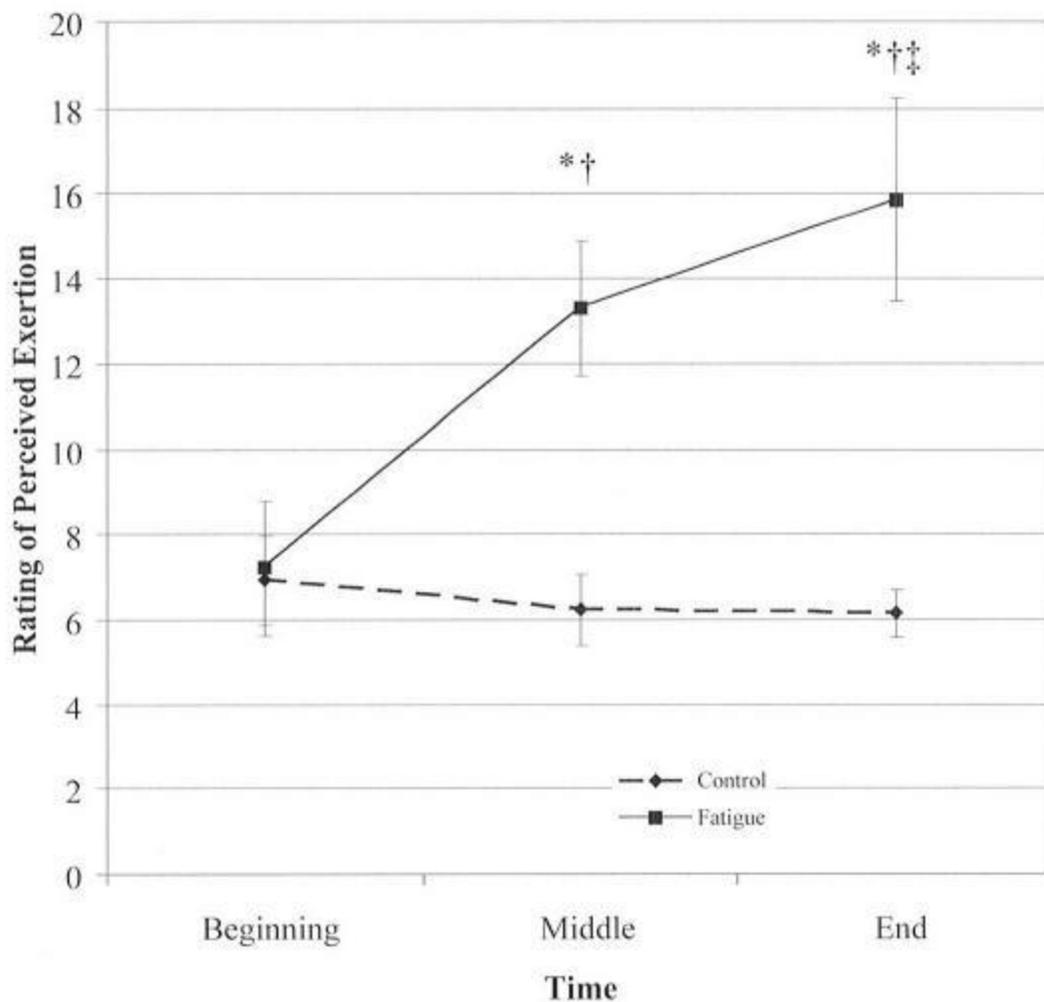


Figure 3. Ratings of Perceived Exertion (RPE) scores at the beginning, middle, and end of the intervention. *Significantly different from control. †Significantly different from beginning. ‡Significantly different from middle.

Ratings of Perceived Exertion. One potential limitation to studies of central fatigue is the ability to quantify the amount of fatigue to which the subjects are subjected. It would be difficult to compare the effect of fatigue on postural stability if the degree of fatigue varied across investigations. To rectify this, several groups, including ours, have used the Borg RPE scale in an attempt to quantify the amount of fatigue. 16,26,31,32 Because perceived exertion and $\dot{V}O_2^{\max}$ are highly correlated, the RPE scale may be used as a substitute to determine exercise intensity.33 Nardone et al26 employed the 10-point Borg RPE scale and found that their protocol elicited perceived exertion that was classified between 5 and 7 (strong to very strong). Using the 15-point Borg RPE scale, Seliga et al16 showed perceived-exertion scores increased significantly with an increase in workload. The RPE values ranged from 9 to 10

during a light workload to 11 to 12 during a moderate workload to 14 to 16 during a heavy workload. They also noted that sway values were higher after exercise at higher workloads.

Other investigators have correlated RPE with percentage of maximum heart rate reserve, percentage of ventilatory threshold, or percentage of $\dot{V}O_2^{\max}$ during various exercise tasks.^{31,32} In a group of physically active males, RPE was measured during a treadmill exercise, cycle exercise, and simulated ski exercise at 70%, 80%, and 90% $\dot{V}O_2^{\max}$.³¹ The RPE values ranged from 13 to 14.2 at 70% $\dot{V}O_2^{\max}$ across the exercise modes to 15.4 to 16 at 80% and 18 to 18.2 at 90%.³¹

Similarly, RPE has been recorded during 10-minute graded cycle-ergometer testing in males (25.3 ± 2.0 years) in relation to ventilatory threshold.³² The RPE values were 10.2 ± 1.2 at the 5-minute mark of an exercise at 80% ventilatory threshold (heart rate = 124.6 ± 14.3 beats/minute) and 15.8 ± 1.7 at the 10-minute mark of exercise at 120% ventilatory threshold (heart rate = 168.9 ± 13.5 beats/minute).³²

The RPE values noted in the aforementioned investigations are similar to our findings of 13.3 ± 1.6 and 15.9 ± 2.4 during the middle and end of our fatigue protocol, respectively. Therefore, we feel confident that, during our protocol, subjects were working at a level greater than 60% $\dot{V}O_2^{\max}$, and the decrease in BESS performance noted during the posttest was a result of their fatigue.

Fatigue and Balance. Although fatigue's effect on balance has most often been studied using force-platform systems, one group studied the influence of a fatigue protocol on BESS performance. Crowell et al²¹ found a decrease in BESS performance after a fatigue protocol consisting of a series of squat jumps, sprints, and treadmill running. Although our exertion protocol did include a number of different exercises, our results immediately after the end of our fatigue protocol concur with those of previous researchers with respect to total BESS score. In addition, the effects of fatigue appear to be condition specific, concurring with previously reported findings that showed fatigue had more of an effect with the tandem-foam and tandem-tremor conditions.²¹

With respect to the different stances and surfaces used in the BESS, our results demonstrated a significant time \times stance \times group interaction. When this interaction was further analyzed, we found that fatigue did not affect either group when performing the double-leg stance conditions. It is likely that the double-leg stance was too easy for our subjects because they did not score many errors, regardless of the level of fatigue. With respect to the single-leg stance, the fatigue group scored more errors than the control group at both the pretest and posttest; however, pretest and posttest scores were not significantly different in either group. A plausible explanation is that the single-leg stance is the most difficult of the 3 stances, and subjects usually have difficulty performing this stance regardless of fatigue level. Previous investigators have also found that subjects perform more poorly on the single-leg condition than on the double-leg or tandem conditions.²² Our fatigue group did score more errors on the tandem-stance conditions during the posttest than the control group. This finding can be attributed to an increase in errors within the fatigue group from pretest to posttest, likely due to fatigue, and a decrease in errors in the control group, likely due to a practice effect. The tandem stance is susceptible to practice effects

after repeat administration of the BESS11,22 and tilt-board postural stability tests.³⁴ Thus, fatigue can influence the various stances in different ways, from no influence on the double-leg stance to a significant influence on the tandem condition.

In addition, our finding that balance decreases after fatigue has been demonstrated in investigations using various methods of causing central fatigue and different measures of postural stability. Using varied fatigue protocols, several authors have found decreases in postural stability as measured by stabilometry.^{16-18,26} Nardone et al¹⁸ noted significant increases in sway path in both eyes-open and eyes-closed conditions and increases in sway area in eyes-closed conditions only after a 25-minute treadmill run. In addition, a 25-minute cycle-ergometer exercise elicited a significant increase in sway area and sway path with the eyes closed and an increase in sway path with the eyes open but to a lesser extent than after the treadmill exercise.¹⁸ A subsequent follow-up investigation using a 25-minute uphill treadmill walk also demonstrated an increase in sway path and sway area in both visual conditions after the exercise.²⁶

Similarly, using the EquiTest to measure postural stability after a 25-km run, Lepers et al¹⁹ found a significant decrease in posttest postural stability for all conditions except the fixed-support, eyes-open condition. Balance performance decreased the most during the sway-referenced, eyes-closed condition (condition 5) and the sway-referenced-sway-referenced condition (condition 6), when the subjects needed to rely on vestibular input as their only accurate sensory input. In addition, the sensory isolation ratios for vision (4:1) and vestibular (5:1) inputs decreased after the exercise protocol, indicating that the subjects did not make effective use of either of these inputs after fatigue.¹⁹

Not all researchers of central fatigue and postural stability have demonstrated a decrease in postural stability after exercise. Contrary to our results, Derave et al²⁵ found no change in center-of-pressure velocity after a 2-hour cycle protocol, indicating that the exercise bout did not elicit decreases in postural stability. They did, however, show a significant exercise \times hydration status interaction. Posttest results demonstrated higher center-of-pressure velocities when subjects were not given fluid replacement during the exertion protocol. It should be noted that their posttest took place 20 to 30 minutes after the end of the 2-hour cycle bout, thereby allowing some recovery time before the posttest. We did not control for hydration status before the exertion protocol; however, our subjects were not given any fluids during or immediately after the protocol.

The factors that could potentially cause a decrease in balance performance after fatigue focus on both central and local means of fatigue. Central, or whole-body, fatigue refers to a decrease in the central nervous system output to the muscles³³ and likely has a component that includes factors responsible for the sense of effort in addition to the alterations in motor pathways.³⁵ Localized muscle fatigue is induced by a decrease in the metabolic substrates available for muscle contraction, such as adenosine triphosphate, creatine phosphate, and glycogen, as well as an increase in metabolites, including lactic acid, in the muscle, resulting in an inability to maintain a desired muscular force output.³⁶ Although we had our subjects perform a fatigue protocol designed to induce central fatigue and did not specifically fatigue a particular muscle group, changes in postural stability after fatigue may result from a combination of central and

localized means.¹⁶ Because balance depends upon the central nervous system and on the 3 sensory systems (visual, vestibular, and somatosensory), alterations in central nervous system ability due to fatigue will likely affect one's ability to maintain balance.

Practice Effect. We also found a significant decrease in the number of BESS errors in our control group after the rest period. This decrease in BESS error scores points to a practice effect in that performance was improved after previous exposure to the balance task. Previous authors have found both practice (short-term)^{11,22,37} and learning^{11,37} effects after serial administration of the BESS. However, these improvements in BESS performance occurred with the third administration, whereas the improvements in our subjects' scores occurred with the second administration.

CLINICAL RELEVANCE

Because the BESS is often used as part of an overall concussion-assessment protocol,^{7,9,10,38} our findings suggest some implications of using the BESS during the initial evaluation of an athlete with a concussion. Often, the BESS is administered on the sidelines immediately after the injury to obtain a time-of-injury measure of postural stability. In most cases, the athlete has just come off the field and is fatigued to some extent. Based on our findings, it would be contraindicated to administer the BESS during this initial time period, when the effects of the concussion might be clouded by the effects of fatigue. In this situation, the athlete might score a surprisingly high number of errors due to the combined effects of the injury and fatigue, and the clinician would not have an accurate record of postinjury postural stability. We cannot conclusively offer a time period in which the effects of fatigue would have diminished, but some authors have demonstrated a return to baseline balance levels after 20 minutes of rest.^{18,25,26,28,34} Therefore, the athletic trainer could perform other aspects of the concussion-assessment protocol first, followed by the BESS. Future investigators should address when error scores return to baseline after fatigue to give clinicians an evidence-based timeline for administering the BESS after injury. Finally, clinicians should be aware that the evaluation of postural stability after MHI is only one small part of the assessment puzzle and should be used along with a symptom checklist, complete neurologic examination, and mental-status testing before a return-to-play decision is made.

REFERENCES

1. Lee CT. Sharpening the sharpened Romberg. *S Pacific Underwater Med Soc J.* 1998;28:125-132.
2. Guskiewicz KM, Perrin DH. Research and clinical applications of assessing balance. *J Sport Rehabil.* 1996;5:45-63.
3. Guskiewicz KM, Perrin DH, Gansneder BM. Effect of mild head injury on postural stability in athletes. *J Athl Train.* 1996;31:300-306.
4. Guskiewicz KM, Riemann BL, Perrin DH, Nashner LM. Alternative approaches to the assessment of mild head injury in athletes. *Med Sci Sports Exerc.* 1997;29:S213-S221.
5. Riemann BL, Guskiewicz KM. Assessment of mild head injury using measures of balance and cognition: a case study. *J Sport Rehabil.* 1997; 6:283-289.
6. Riemann BL, Guskiewicz KM, Shields EW. Relationship between clinical and forceplate measure of postural stability. *J Sport Rehabil.* 1999;8:71-82.
7. Riemann BL, Guskiewicz KM. Effects of mild head injury on postural stability as measured

- through clinical balance testing. *J Athl Train.* 2000; 35:19-25.
8. Arnold BL, Schmitz RJ. Examination of balance measures produced by the Biodex Stability System. *J Athl Train.* 1998;33:323-327.
 9. Guskiewicz KM. Postural stability assessment following concussion: one piece of the puzzle. *Clin J Sport Med.* 2001;11:182-189.
 10. Guskiewicz KM, Ross SE, Marshall SW. Postural stability and neuropsychological deficits after concussion in collegiate athletes. *J Athl Train.* 2001;36:263-273.
 11. Valovich TC. The Use of the Standardized Assessment of Concussion and Balance Error Scoring System and Learning Effects in Youth Sports Participants [dissertation]. Charlottesville, VA: University of Virginia; 2002.
 12. Alderton AK, Moritz U. Does calf-muscle fatigue affect standing balance? *Scand J Med Sci Sports.* 1996;6:211-215.
 13. Lundin TM, Fuerbach JW, Grabiner MD. Effect of plantar flexor and dorsiflexor fatigue on unilateral postural control. *J Appl Biomech.* 1993; 9:191-201.
 14. Ochsendorf DT, Mattacola CG, Arnold BL. Effect of orthotics on postural sway after fatigue of the plantar flexors and dorsiflexors. *J Athl Train.* 2000;35:26-30.
 15. Skinner HB, Wyatt MP, Hodgdon JA, Conrad DW, Barrack RL. Effect of fatigue on joint position sense of the knee. *J Orthop Res.* 1986;4:112-118.
 16. Seliga R, Bhatlacharya A, Succop P, Wixkstrom R, Smith D, Willeke K. Effect of work load and respirator wear on postural stability, heart rate, and perceived exertion. *Am Ind Hyg Assoc J.* 1991;52:417-422.
 17. Thomas JR, Gotten DJ, Spieth WR, Abraham NL. Effects of fatigue on stabilometer performance and learning of males and females. *Med Sci Spans.* 1975;7:203-206.
 18. Nardone A, Tarantola J, Giordano A, Schieppati M. Fatigue effects on body balance. *Electroencephalogr Clin Neurophysiol.* 1997;105:309-320.
 19. Lepers R, Bigard AX, Diard JP, Gouteyron JF, Guezennec CY. Posture control after prolonged exercise. *Enr J Appl Phystol Occup Physiol.* 1997; 76:55-61.
 20. Hoffman M, Schrader J, Applegate T, Koceja D. Unilateral postural control of the functionally dominant and nondominant extremities of healthy subjects. *J Athl Train.* 1998;33:319-322.
 21. Crowell DH, Guskiewicz KM, Prentice WE, Onate JA. The effect of fatigue on postural stability and neuropsychological function [abstract]. *J Athl Train.* 2001;36:S-33.
 22. Valovich TC, Perrin DH, Gansneder BM. Repeat administration elicits a practice effect with the Balance Error Scoring System but not with the Standardized Assessment of Concussion in high school athletes. *J Athl Train.* 2003;38:51-56.
 23. Borg G. Perceived exertion as an indicator of somatic stress. *Scand J Rehabil Med.* 1970;2:92-98.
 24. Borg GAV. Psychophysical bases of perceived exertion. *Med Sci Sports Exen:* 1982;14:377-381.
 25. Derave W, De Clercq D, Bouckaert J, Pannier JL. The influence of exercise and dehydration on postural stability. *Ergonomics.* 1998;41:782-789.
 26. Nardone A, Tarantola J, Galante M, Schieppati M. Time course of stabilometric changes after a strenuous treadmill exercise. *Arch Phys Med Rehabil.* 1998;79:920-924.
 27. Johnston RB III, Howard ME, Cawley PW, Losse GM. Effect of lower extremity muscular fatigue on motor control performance. *Med Sci Sports Exerc.* 1998;30:1703-1707.
 28. Yaggie JA, McGregor S, Armstrong CW. The effects of osokinetic fatigue on balance and

- the ranges of postural control [abstract]. *Med Sci Sports Exerc.* 1999;31:S284.
29. Vuillerme N, Nougier V, Prieur JM. Can vision compensate for a lower limbs muscular fatigue for controlling posture in humans? *Neurosci Lett.* 2001;308:103-106.
30. Sparto PJ, Parnianpour M, Reinsel TK, Simon S. The effect of fatigue on multijoint kinematics, coordination, and postural stability during a repetitive lifting test. *J Orthop Sports Phys Ther.* 1997;25:3-12.
31. Robertson RJ, Moyna NM, Sward KL, Millich NB, Goss FL, Thompson PD. Gender comparison of RPE at absolute and relative physiological criteria. *Med Sci Sports Exerc.* 2000;32:2120-2129.
32. Mahon AD, Duncan GE, Howe CA, Del Corral P. Blood lactate and perceived exertion relative to ventilatory threshold: boys versus men. *Med Sci Sports Exerc.* 1997;29:1332-1337.
33. Brooks GA, Fahey TD, White TP. *Exercise Physiology*. Mountain View, CA: Mayfield Publishing Co; 1996.
34. Westcott SL, Crowe TK, Deitz JC, Richardson P. Test-retest reliability of the Pediatric Clinical Test of Sensory Interaction for Balance. *Phys Occup Ther Pediatr.* 1994;14:1-22.
35. McComas AJ. *Skeletal Muscle: Form and Function*. Champaign, IL: Human Kinetics; 1996:230-231.
36. Rozzi S, Yuktanandana P, Pincivero D, Lephart SM. Role of fatigue on proprioception and neuromuscular control. In: Lephart SM, Fu FH, eds. *Proprioception and Neuromuscular Control in Joint Stability*. Champaign, IL: Human Kinetics; 2000:375-383.
37. Mancuso JJ, Guskiewicz, KM, Onate JA, Ross SE. An investigation of the learning effect for the Balance Error Scoring System and its clinical implications (abstract). *J Athl Train.* 2002;37:S-10.
38. Guskiewicz. KM. Balance and mild head injury in athletes. *Orthop Phys Ther Clin North Am.* 2002;11:143-158.