Evaluation of Multifrequency Bioelectrical Impedance Analysis in Assessing Body Composition of Wrestlers

ALAN C. UTTER and PAMELA G. LAMBETH

Department of Health, Leisure, and Exercise Science, Appalachian State University, Boone, NC

ABSTRACT

UTTER, A. C. and P. G. LAMBETH. Evaluation of Multifrequency Bioelectrical Impedance Analysis in Assessing Body Composition of Wrestlers. *Med. Sci. Sports Exerc.*, Vol. 42, No. 2, pp. 361–367, 2010. **Mục đích**: Để đánh giá độ chính xác của phân tích trở kháng điện sinh học đa tần số (MFBIA) trong việc đánh giá khối lượng không có chất béo (FFM) so với cân thủy tĩnh (HW) và Đo bề dày nếp da (SK) ở các đô vật ở trường trung học ở trạng thái hydrat hóa. **Phương pháp**: Thành phần cơ thể được xác định bởi MFBIA, HW, và SK 3 vùng trong 72 đô vật trung học (mean ± SD; Tuổi = 15.3 ± 1.4, Chiều cao = 1.71 ± 0.08 m, Cân nặng = 67.3 ± 13.4 kg). Trạng thái hydrat hóa được định lượng bằng cách đánh giá trọng lượng riêng của nước tiểu. **Kết quả**: Không có sự khác biệt đáng kể về FFM ước tính giữa MFBIA (57,2 ± 9,5 kg) và HW (57,0 ± 10,1 kg) hoặc SK (56,4 ± 8,8 kg). SEE cho FFM với HW làm phương pháp tham chiếu là 2,73 kg đối với MFBIA và 2,66 kg đối với SK. Mối tương quan đã được tìm thấy cho FFM giữa HW và MFBIA ($r = 0,96$, $P <0,001$) và giữa HW và SK ($r = 0,97$, $P <0,001$). Một thiên vị hệ thống đã được tìm thấy cho MFBIA vì sự khác biệt giữa MFBIA và HW tương quan với trung bình FFM của hai phương pháp ($r = -0,22$, $P <0,001$). Một sai lệch cũng đã được nhìn thấy giữa SK và HW và tương quan với mức trung bình FFM ($r = -0,47$, $P G 0,001$). **Kết luận**: Nghiên cứu này chứng minh rằng MFBIA cung cấp các ước tính tương tự về FFM khi so sánh với HW trong một quần thể đấu vật ở trường trung học không đồng nhất trong trạng thái hydrat hóa. MFBIA là một công cụ đánh giá hấp dẫn, dễ sử dụng và có thể được coi là một phương pháp thay thế dựa tại trận để ước tính FFM của các đô vật trung học.

Key Words: WRESTLING, FAT-FREE MASS, MINIMUM WRESTLING WEIGHT, BODY FAT, BIOELECTRICAL IMPEDANCE

According to the National Federation of State High School Associations' annual survey, there were 259,688 wrestlers participating on more than 10,000 teams during the 2007–2008 wrestling season (www.nfhs.org). This is accompanied by a 6.8% increase in the number of teams, causing the national total of high school wrestling teams to escalate to more than 10,000 (www.nfhs.org). An increase in the growth of the sport coupled with the recent implementation of a mandatory wrestling weight certification program (WCP) intensifies the need for a practical and valid field-based method of body composition testing among the wrestling com- munity. The WCP enforced by the National Federation of State High School Associations came about to minimize unhealthy and dangerous weight loss practices of high

school wrestlers. After observing the effectiveness of the National Collegiate Athletic Association's (NCAA) imple- mentation of a WCP (22), the goal was for every high school in the United States to have executed a WCP by the 2006–2007 wrestling season. The NCAA mandated an obligatory WCP 10 yr ago (during the 1998–1999 season) after the deaths of three collegiate-level wrestlers within a 5-wk period in 1997 (6,10).

The protocol for assessing a minimum wrestling weight (MWW) uses the athlete's body mass, body composition, and urine specific gravity. The measured fat-free mass (FFM) is then used to calculate each wrestler's MWW at 5% body fat for the collegiate level and 7% body fat for the high school level (20). Although methods of assessing hydration and body composition have been established by the NCAA, at the high school–level individual, state high school athletic associations are responsible for determining their own acceptable methods. Skinfolds (SK) have long been seen as a valid and practical method for body com- position assessment in high school wrestling programs (20,27); however, this method does impart some practical limitations. These include having access to enough trained assessors within a defined geographical region, technical error that may be present because of caliper performance, within-tester and between-tester differences in SK com- pressibility, and the inability to palpate the fat–muscle in- terface (12,16,17). Variations in SK compression have been

attributed to factors such as subcutaneous fat thickness, state of hydration, and the distribution of fibrous tissue and blood vessels (12). State high school athletic associa- tions are receptive to methods that are equivalent to the SK measurements in ease of use, accessibility, cost, validity, and reliability. Other methods to estimate body composition include dual x-ray absorptiometry (DXA), hydrostatic weighing (HW), single-frequency leg-to-leg bioelectrical impedance analysis (SFBIA), ultrasound, air displacement plethysmography (ADP), and near-infrared light interaction (1,8,12,18,19,26,28,29,31,32). Access to and cost of both DXA and HW pose practical limitations for state high school athletic associations in using these methods when assessing body composition of high school wrestlers. Multi- frequency bioelectrical impedance analysis (MFBIA) has also been demonstrated to be an alternate method to mea- sure body composition (7,15,23–25).

Whereas SFBIA uses only one frequency (50 kHz) to measure impedance via surface electrodes on the hand and foot, a leg-to-leg MFBIA incorporates multiple frequencies, measuring impedance at 0, 1, 5, 50, 100, and 200 to 500 kHz (15). By introducing different frequencies, FFM, total body water (TBW), intracellular water, and extracellular water can be estimated (15). MFBIA is based on the theory that lower frequencies (G50 kHz) are conducted within the ex- tracellular compartment and that higher frequencies, defined as greater than 200 kHz, can measure intracellular space by passing through the cell membrane. Intracellular and ex- tracellular water can be measured separately because of the changing direction of electrical impulses when the frequen- cy of the signal is changed (24). Previous research on the validation of MFBIA to estimate TBW and acute changes in TBW have demonstrated positive results (11,14,33). The estimated amount of total body water is based on the con- stant relationship that there is 73.2% water in lean body mass(34). Therefore, an accurate estimate of TBW will im- prove the validity of FFM measurements and subsequent body fat values.

Multifrequency bioelectrical impedance analysis is rela- tively new with its introduction in the late 1980s; an earlier study done in 1989 determined that MFBIA failed to estimate TBW accurately in the trunk, where impedance is relatively low (4). Pietrobelli et al. (23) conducted a study that demonstrated that MFBIA was superior to SFBIA in estimating FFM when compared with the DXA. That investigation evaluated 49 healthy, nonexercising males and females without serious medical conditions. Results demonstrated significant correlations between DXA and MFBIA of arm skeletal muscle R^2 = 0.91, SEE = 0.57 (kilograms of FFM), P G 0.01. Previous research has also demonstrated that arm-to-leg SFBIA (21) and leg-to-leg SFBIA (31) are acceptable methods for establishing minimal weight in interscholastic wrestlers.

In another more recent investigation, 40 male subjects from a subpopulation of a weight loss/maintenance study underwent HW, DXA, and segmental MFBIA (5, 50, 250,

and 500 kHz) for comparison of FFM, body fat percentage (%BF), and fat mass (24). The results from that study de- monstrated a high correlation between MFBIA with DXA (r = 0.94, P G 0.01) and HW (r = 0.94, P G 0.01), sug- gesting that MFBIA is an acceptable method for assessing segmental distribution of FFM (24).

To our knowledge, no previous studies have investigated the validity of MFBIA in determining body composition in high school wrestlers. Therefore, the purpose of this study was to evaluate the accuracy of MFBIA (5, 50, and 500 kHz) method for measuring FFM when compared with HW and SK in high school wrestlers. SK measures were included for comparative purposes because SK measures are com- monly used to assess body composition in high school wrestlers. We hypothesized that there would be no signifi- cant differences between MFBIA or SK and HW for the estimation of FFM.

METHODS

Subjects. Subjects were male interscholastic wrestlers from three North Carolina high schools (N = 72). The athletes ranged in age from 12 to 18 yr, height from 1.4 to 1.9 m, and body mass from 39.6 to 99.8 kg. Please refer to Table 1, which includes the mean (TSD) values for age, height, and body mass in addition to the range values mentioned. Subjects were representative of all the high school weight categories with the exception of heavy- weight. The heavyweight wrestlers were excluded because they typically do not have weight loss concerns. Subjects and parents gave written and informed consent, and the experimental procedures were approved by the institutional review board for investigations at Appalachian State University (ASU) and were in compliance with the American College of Sports Medicine policies for use of human subjects.

Testing schedule. All body composition assessments occurred in the Human Performance Laboratory at the ASU. All measurements were made early in the presea- son (October–November) and during the morning hours (8:00 a.m. to 12:00 p.m.) of Saturday. Height was deter- mined using a stadiometer, and body mass was determined using a calibrated digital scale. All body composition mea- surements were performed in a hydrated state. Baseline hydration was established by obtaining a urine sample for

TABLE 1. Subject characteristics (N = 72).

Characteristics	Mean T SD
Age (yr)	15.3 T 1.4
Height (m)	1.71 T 0.08
Body mass (kg)	67.3 T 13.4
Wrestling experience (yr)	3.3 T 2.5
Urine specific gravity	1.01 T 0.01
Residual lung volume (L)	1.45 T 0.4
% body fat (HW)	14.7 T 7.0

measurement of urine specific gravity (U_{sg}) using a hand-held optical refractometer (Atago; National Microscope Exchange, Redmond, WA). All subjects were considered to be adequately hydrated based on an U_{sg} e 1.025 g|mL⁻¹ (3).

During each testing session, the subject's body composition was evaluated by three different methods in the following succession: 1) SF analysis, 2) MFBIA, and 3) HW.

SK testing. SK measures were done with Lange SK calipers at three sites: triceps, subscapular, and abdomen. The SK calipers were calibrated to 10 g|mm⁻² by the manufacturer. SK were measured three times at each site to the nearest 0.5 mm with the mean value recorded. All SK measurements were taken on the right side of the body. The triceps SK was measured vertically in the midline of the posterior aspect of the upper arm, midway between the lateral acromion process of the scapula and the inferior margin of the olecranon process of the ulna. The subscapular SK was measured as a diagonal fold just below the inferior angle of the scapular toward the right side of the body. The abdomen SK was raised vertically on the right side of abdomen 3 cm from the midpoint of the umbilicus (16). There was only one SK assessor who is highly trained and experienced in measuring SK of wrestlers with a test–retest reliability of consistently r 9 0.90. Body density (D_b) was determined from the three SK measures using the prediction equation $D_b = [1.0982 \_j \text{ (sum SK)} \times 0.000815] + [(\text{sum SK})^2 \times 0.00000084]$ validated by Lohman (16). %BF was determined from D_b using the equation of Brozek et al. (5). This %BF equation was also used with the D_b determined from HW.

HW. D_b was also determined by HW. HW was performed in a custom-built stainless steel tank, with three load cells interfaced to a computer (Exertech Fitness Equipment, Dresbach, MN). During HW, the subject was asked to expel as much air as possible from his lungs during complete submersion. After 5–10 trials, the highest underwater weight that could be repeated within 100 g by the subject was averaged and recorded. After completion of the HW trials, residual volume was measured (outside the tank) by the oxygen dilution method using the procedures described by Wilmore et al. (35). A minimum of two trials were completed with the two closest readings within 10% being averaged to calculate residual volume.

MFBIA. MFBIA measurements were determined using the InBody 520 (Biospace Co., Beverly Hills, CA). Subjects were measured for MFBIA standing erect and fully hydrated. The InBody 520 body fat analyzer measures impedance across both legs, arms, and the trunk via multiple frequencies of 5, 50, and 500 kHz. The system's eight electrodes are in the form of footpads mounted on the surface of a platform scale and in handheld pads in handles extending out from the machine's body. Each footpad is divided in half so that the anterior and posterior portions form two separate electrodes. Each handle of the machine has two separate electrodes as well, one in contact with the thumb and the other in contact with the palm. These electrodes are connected to the current and voltage supply of the device. Impedance and body mass are automatically measured, and the subject's height and age are manually entered into the system. The device is regulated by an internal microprocessor that measures impedance from each body segment in a particular order and regulates the varying frequencies. Segmental impedance, TBW, extracellular water, intracellular water, and body mass are all measured simultaneously as the subject's bare feet and palm and thumbs make pressure contact with the electrodes and digital scale. FFM was calculated using the equations supplied by the manufacturer.

Statistical analysis. Multiple paired-sample t-tests with Bonferroni adjustment (P G 0.025) were performed to examine body composition differences. Values are expressed as means T SD. To assess the agreement in FFM measured by MFBIA and SK versus HW, linear regression and Bland–Altman analyses were conducted. Linear regression analyses were performed with FFM by HW as the dependent variable to determine whether the regression line differed significantly from the line of identity (slope = 1, intercept = 0). In the Bland–Altman plots, bias was calculated as the mean difference between methods, and the 95% limits of agreement were calculated as the bias T 2SD of the differences between methods (2).

The SEE obtained from the linear regression model and the prediction error (PE) representing the average deviation of individual variables from the line of identity ($y = x$) were also used to compare FFM measurement by MFBIA and HW (13). For all tests, statistical significance was accepted at P G 0.05.

RESULTS

The characteristics of the study subjects are presented in Table 1. The sample consisted of 72 high school wrestlers who were moderately experienced, with an average of 3.29 yr of wrestling experience. Table 2 presents the FFM data (mean T SD) and the relation between MFBIA and SK to HW for the sample. There was a strong correlation ($r = 0.96$ and $r = 0.97$) and no significant differences in mean FFM predicted by MFBIA (57.2 T 9.5) or SK (56.4 T 8.8) and the criterion HW (57.0 T 10.1).

Figures 1 and 2 illustrate the regression analysis when HW is the dependent variable (y-axis) and the prediction method is the independent variable (x-axis). Normal distribution of the data was confirmed by evaluating the skewness and kurtosis. A good SEE and high adjusted R^2

TABLE 2. Comparison of FFM between MFBIA and SK with HW ($n = 72$).

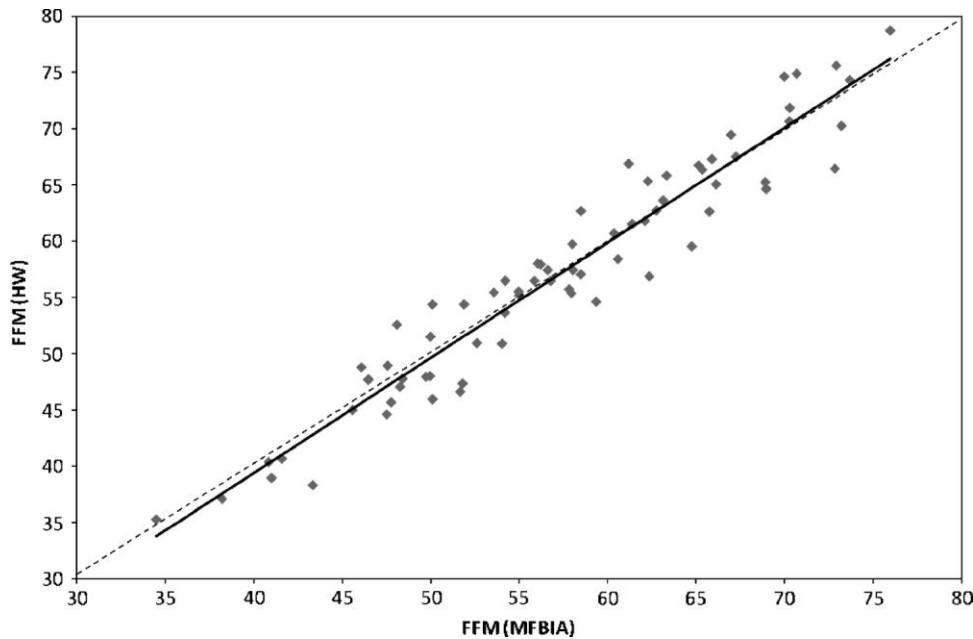| Method	FFM (kg)	R	MD (kg)	SEE (kg)	PE (kg)
HW	57.0 T 10.1				
SK	56.4 T 8.8	0.97	_j 0.6 T 2.8	2.66	2.89
MFBIA	57.2 T 9.5	0.96	0.2 T 2.7	2.73	2.73

FIGURE 1—Comparison of FFM determined by HW and MFBIA in high school wrestlers. Linear regression ($y = 1.0245x$ j 1.6124, adjusted R^2 = 0.93, SEE = 2.73 kg, P G 0.001). *Solid line* indicates line of best fit. *Dashed line* indicates line of identity.

resulted from both MFBIA and SK compared with the criterion HW. Small nonsignificant mean differences were found between the methods in estimating FFM: (MFBIA j HW = 0.2 T 2.7 kg) and (SK j HW = j 0.6 T 2.8 kg).

To evaluate systematic bias, Figures 3 and 4 illustrate the Bland–Altman plot of the difference between FFM measured by MFBIA or SK and HW versus the average FFM by the two methods. The regression lines of the Bland–

Altman plots indicated a significant negative correlation for both MFBIA (r = j 0.22, P G 0.001) and SK (r = j 0.47, P G 0.001).

DISCUSSION

Results from this investigation demonstrated that the MFBIA (InBody 520) system estimates FFM within an

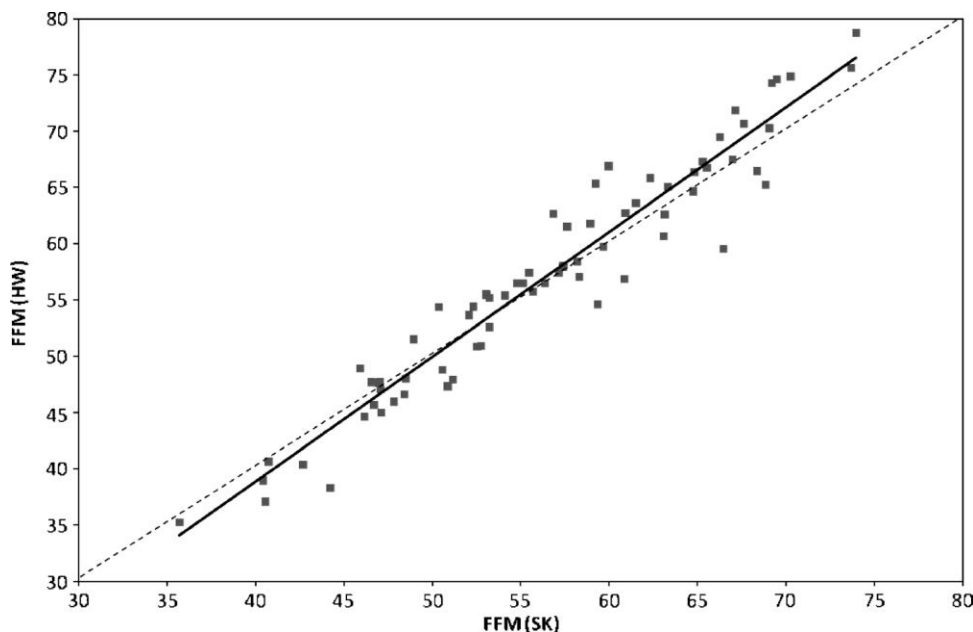FIGURE 2—Comparison of FFM determined by HW and SK analysis in high school wrestlers. Linear regression ($y = 1.11x$ j 5.5883, adjusted R^2 = 0.94, SEE = 2.66 kg, P G 0.001). *Solid line* indicates line of best fit. *Dashed line* indicates line of identity.
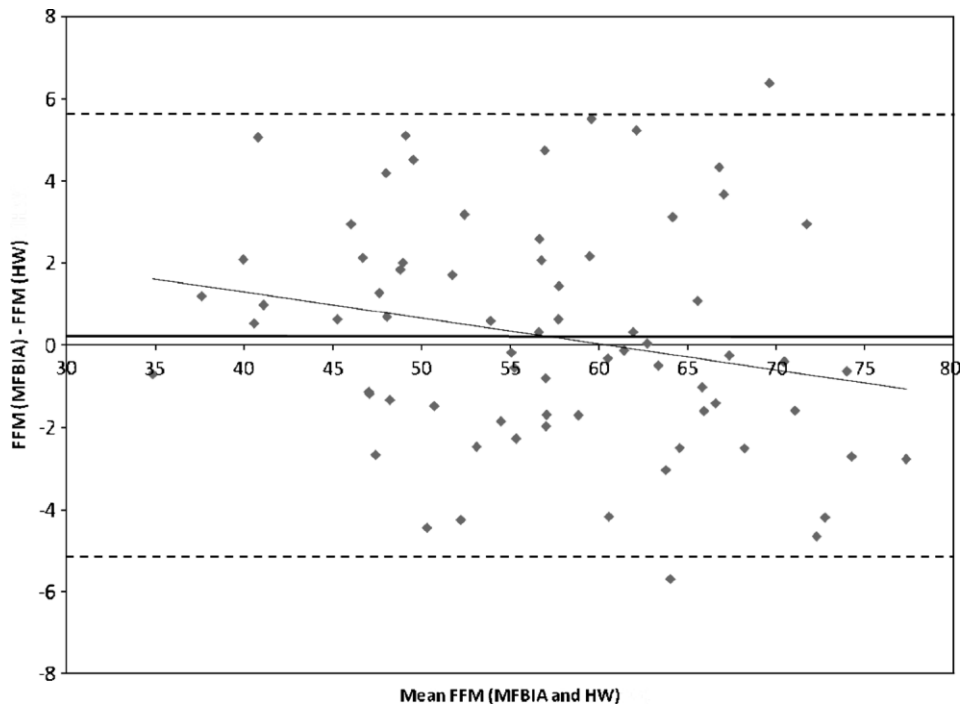
FIGURE 3—Bland–Altman plot of the difference between FFM measured by HW and MFBIA. The *light solid line* indicates line of best fit, the *heavy solid line* indicates the mean difference, and the *dotted lines* (mean difference T 2SD) indicate upper and lower 95% limits of agreement.

acceptable range when compared with HW in high school wrestlers. There were no significant differences in mean FFM predicted by MFBIA and the criterion HW. The SEE and PE values of FFM were in the ''very good'' range (2.73 kg) (13). Please refer to Table 2 for the SEE and PE values. When examining systematic bias using the Bland–

Altman plot, a significant correlation was found between the difference of FFM measured by MFBIA and HW versus the average FFM by the two methods. Therefore, across the body mass range, there was a systematic bias to overestimate FFM of wrestlers in the lighter weight classes when using MFBIA and to underestimate FFM of those in the
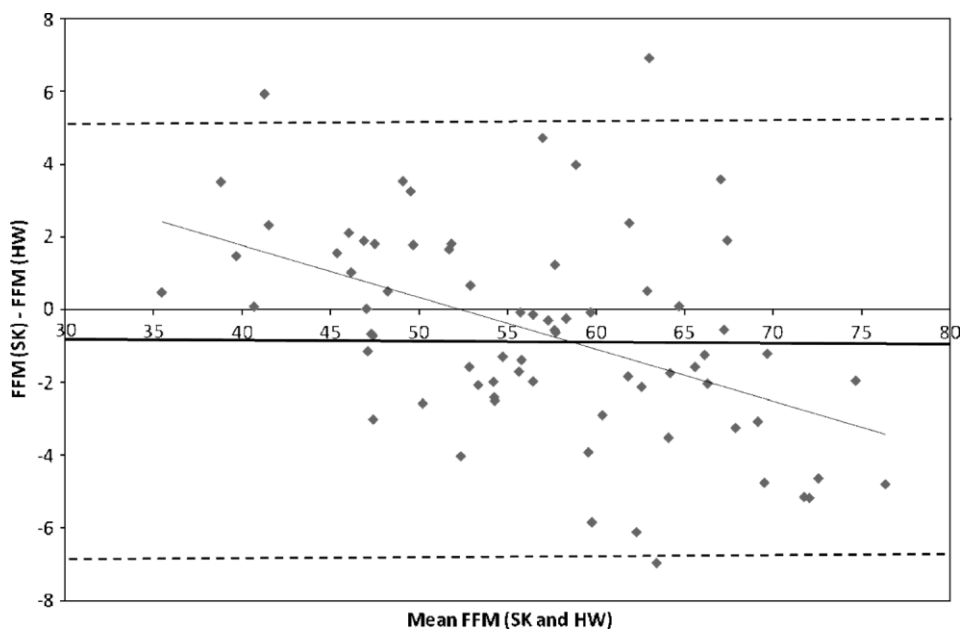

FIGURE 4—Bland–Altman plot of the difference between FFM measured by HW and SK. The *light solid line* indicates line of best fit, the *heavy solid line* indicates the mean difference, and the *dotted lines* (mean difference T 2SD) indicate upper and lower 95% limits of agreement.

upper weight classes when using MFBIA (Fig. 3). Interestingly, a similar significant negative correlation and subsequent systematic bias was also found for SK when compared with HW within this cohort (Fig. 4).

This is the first investigation to compare estimations of FFM from the MFBIA (InBody 520; Biospace Co.) system to HW in heterogeneous high school wrestling population. The size of the sample studied and its physical characteristics make it a representative sample of high school wrestlers (22,31). Therefore, results from the present investigation may be of value concerning wrestling WCP established by state high school athletic associations who are considering other methods to assess body composition and MWW. The SEE value for MFBIA (2.73 kg) found in the present study is comparable to other field-based mea- sures of body composition in wrestlers: 1.72–1.97 kg for SK (8,31), 2.3 kg for ultrasound (30), and less than for SFBIA (3.5 kg) (9,31). In practical terms, the results of this study demonstrated that MFBIA predicted FFM within 2.73 kg (6.0 lb) 68% of the time and within 5.48 kg (12.0 lb) 95% of the time. The average amount of weight between high school weight classes varies from 2.27 to 11.79 kg (5–26 lb) excluding heavyweight. MFBIA compares slightly better than SFBIA, another field-based measure that predicts FFM within 3.64 kg (8.0 lb) 68% of the time and within 7.3 kg (16.0 lb) 95% of the time in a sample of 129 high school wrestlers (31). In addition, a newer technology, ultrasound, predicted FFM within 2.31 kg (5.0 lb) 68% of the time and within 4.5 kg (10 lb) 95% of the time in a sample of 70 high school wrestlers (30). In the present study, when examining the MWW as determined by the criterion HW results demonstrated that 40% and 39% of the subjects were correctly classified when using MFBIA and SK, respectively. Although HW, ADP, and DXA have been considered the criterion standard for minimal wrestling weight assessment, these are clearly not practical for use when testing a large cohort of wrestlers. Because wrestling is the only sport in the United States that mandates body composition measurement before competition coupled with an increase in participation, assessment and validation of new technologies are clearly warranted. Choosing an appropriate method to assess body composition becomes an important objective of the health care provider and the state high school athletic associations. When state high school athletic associations determine which body composition method(s) to use when implementing a wrestling WCP, the following factors should be evaluated: 1) accuracy and precision (validity), 2) cost, 3) competitive equity, 4) practicality, 5) ease of use and administration, and 6) safety.

Results of the present investigation are consistent with previous research evaluating MFBIA in other populations. Salmi (24) investigated 40 male subjects from a subpopulation of participants in a weight loss maintenance study, ranging in body mass index from 24.9 to 40.7 kg·m^{-2} and age from 36 to 53 yr. In that study, a significant correlation of FM ($r = 0.94$), FFM ($r = 0.88$), and %BF ($r = 0.88$) between DXA and MFBIA was found. Pietrobelli et al. (23) compared the segmental skeletal muscle from MFBIA, in which a skeletal muscle prediction equation was developed, with that of DXA in 49 healthy Caucasian subjects older 20 yr. The results demonstrated that the correlation ($R^2 = 0.88$) was greater at higher frequency (9300 Hz) for the leg muscle versus any frequency G300 Hz in which variance was significantly lower (R^2 e 0.84). In a study of 15 healthy, active men (%BF = 15.6 T 5.1%) aged 19–25 yr, Stahn et al. (25) measured the muscle volume of the arm and leg using magnetic resonance imaging and MFBIA. Their findings demonstrated that MFBIA was beneficial in estimating lower limb muscle volume of healthy, active adult men producing a mean nonsignificant underestimation of less than 0.5% at both 50 and 500 Hz when comparing magnetic resonance imaging and MFBIA. Considering that previous research with MFBIA has been completed on nonathletic samples, future validation research is clearly warranted in both other wrestling populations (i.e., colle- giate or international) and/or other sport populations in which body composition assessment is deemed important.

When evaluating the Bland–Altman plots for FFM with MFBIA and SK, a systematic bias was found for both methods. The systematic bias found for MFBIA and SK in the present study and previous investigations (30,31) suggests that ''bias'' should be included and evaluated as an outcome variable in future validation studies concerning body composition assessment techniques in wrestlers.

This study demonstrated that FFM values measured by the MFBIA (InBody 520) system were not statistically different when compared with values obtained by HW in a representative high school wrestling population during a hydrated state, and therefore, this method should be considered as an alternative field-based method for determining the minimum weight for wrestlers. As newer technologies to assess body composition are carefully evaluated, one must consider that any field-based method to assess body composition may introduce biological and technical error that will affect the precision of FFM estimation at the individual level. Therefore, caution and careful interpretation of results (including an option for an appeal process) should be a vital component of a wrestling WCP. MFBIA has several advantages: it does not require a high degree of technical skill, making it easy to use; it is safe; it provides simultaneous measures of body mass, body composition, and TBW in a short period; results are instantaneous; and the device is portable. These advantages may make MFBIA attractive to educational institutions that may not have access to trained anthropometrists, HW, ADP, and DXA and to address concerns that have been expressed by coaches, officials, and athletic trainers who question the results of SK testing performed by someone who may not be completely objective or impartial. Pretest guidelines to ensure normal hydration status must be followed to minimize measurement error when using the MFBIA method.

REFERENCES

1. Abe T, Tanaka F, Kawakami Y, et al. Total and segmental subcutaneous adipose tissue volume measured by ultrasound. *Med Sci Sports Exerc*. 1996;28(7):908–12.
2. Altman DG, Bland JM. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*. 1986;8:307–10.
3. Armstrong LE, Maresh CM, Castellani JW, et al. Urinary Indices of hydration status. *Int J Sports Nutr*. 1994;4(3):265–79.
4. Baumgartner RN, Chumlea WC, Roche AF. Estimation of body composition from bioelectrical impedance of body segments. *Am J Clin Nutr*. 1989;50:21–6.
5. Brozek J, Grande F, Anderson JP, Kemp A. Densiometric analysis of body composition: revision of some quantitative assumptions. *Ann NY Acad Sci*. 1963;110:113–40.
6. Center for Disease Control and Prevention. Hyperthermia and dehydration-related deaths associated with intentional rapid weight loss in three collegiate wrestlers—North Carolina, Wisconsin, and Michigan, November–December 1997. *JAMA*. 1998; 279:824–5.
7. Cha K, Shin S, Shon C, et al. Evaluation of segmental bioelectrical impedance analysis (SBIA) for measuring muscle distribution. *J ICHPER SD-ASIA*. 1997;11–4.
8. Clark RR, Bartok C, Sullivan JC, Schoeller DA. Minimum weight prediction methods cross-validated by the four-component model. *Med Sci Sports Exerc*. 2004;36(4):639–47.
9. Clark RR, Bartok C, Sullivan JC, Schoeller DA. Is leg-to-leg BIA valid for predicting minimum weight in wrestlers? *Med Sci Sports Exerc*. 2005;37(6):1061–8.
10. Committee refines wresting safety rules. *The NCAA News*. 1998; 35(16):1.
11. De Lorenzo A, Andreoli A, Deurenberg P. Impedance ratio as a measure of water shifts. *Ann Nutr Metab*. 1997;41:22–8.
12. Fanelli MT, Kucmarski RJ. Ultrasound as an approach to assessing body composition. *Am J Clin Nutr*. 1984;39:703–9.
13. Heyward VH, Wagner DR. *Applied Body Composition Assessment*. 2nd ed. Champaign (IL): Human Kinetics; 2004. p. 27–65.
14. Higgins KJ, Reid PM, Going SB, Howell WH. Validation of bioimpedance spectroscopy to assess acute changes in hydration status. *Med Sci Sports Exerc*. 2007;39(6):984–90.
15. Kyle UG, Bosaeus I, De Lorenzo AD, et al. Bioelectrical impedance analysis—part II: utilization in clinical practice. *Clin Nutr*. 2004;23:1430–53.
16. Lohman TG. Skinfolds and body density and their relation to body fatness: a review. *Hum Biol*. 1981;53:181–225.
17. Morrow JR, Fridye T, Monaghen SD. Generalizability of the AAHPRED health related skinfold test. *Res Q Exerc Sport*. 1986; 57:187–95.
18. Norlander C, Willner J, Hansson GA, et al. Influence of the subcutaneous fat layer, as measure by ultrasound, skinfold calipers, and BMI, on the EMG amplitude. *Eur J Appl Physiol*. 1984;89: 514–9.
19. Oppliger RA, Clark RR, Nielsen DH. New equations improve NIR prediction of body fat among high school wrestlers. *J Orthop Sports Phys Ther*. 2000;30:536–43.
20. Oppliger RA, Harms RD, Herrmann DE, Streich CM, Clark RR. The Wisconsin wrestling minimum weight project: a model for weight control among high school wrestlers. *Med Sci Sports Exerc*. 1995;27(8):1220–4.
21. Oppliger RA, Nielsen DH, Vance DG. Wrestlers' minimal weight: anthropometry, bioimpedance, and hydrostatic weighting compared. *Med Sci Sports Exerc*. 1991;23(2):247–53.
22. Oppliger RA, Utter AC, Scott JR, Dick RW, Klossner D. NCAA rule change improves weight loss among national championship wrestlers. *Med Sci Sports Exerc*. 2006;38(5):963–70.
23. Pietrobelli A, Morini P, Battistini N, Chiumello G, Nunez C, Heymsfield SB. Appendicular skeletal muscle mass: prediction from multiple frequency segmental bioimpedance analysis. *Eur J Clin Nutr*. 1998;52:507–11.
24. Salmi JA. Body composition assessment with segmental multifrequency bioimpedance method. *J Sports Sci Med*. 2003; 2(3):1–29.
25. Stahn A, Terblanche E, Strobel G. Modeling upper and lower limb muscle volume by bioelectrical impedance analysis. *J Appl Physiol*. 2007;103:1428–35.
26. Stolk RP, Wink O, Zelissen PMJ, et al. Validity and reproducibility of ultrasonography for the measurement of intra-abdominal adipose tissue. *Int Obes*. 2001;25:1346–51.
27. Thorland WG, Tipton CM, Lohman TG, et al. Midwest wrestling study: prediction of minimal wrestling weight for high school wrestlers. *Med Sci Sports Exerc*. 1991;23(9):1102–10.
28. Tornaghi G, Raiteri R, Pozzato C, et al. Anthropometric or ultrasonic measurements in assessment of visceral fat? A comparative study. *Int J Obes*. 1994;18:771–5.
29. Utter AC, Goss FL, Swan PD, Harris GS, Robertson RJ, Trone GA. Evaluation of air displacement for assessing body composition of collegiate wrestlers. *Med Sci Sports Exerc*. 2003;35(3): 500–5.
30. Utter AC, Hager ME. Evaluation of ultrasound in assessing body composition of high school wrestlers. *Med Sci Sports Exerc*. 2008; 40(5):943–9.
31. Utter AC, Nieman DC, Mulford GJ, et al. Evaluation of leg-to-leg BIA in assessing body composition of high-school wrestlers. *Med Sci Sports Exerc*. 2005;37(8):1395–400.
32. Utter AC, Scott JR, Oppliger RA, et al. A comparison of leg-to-leg bioelectrical impedance and skinfolds in assessing body fat in college wrestlers. *J Strength Cond Res*. 2001;15:157–60.
33. Van Marken Lichtenbelt WD, Snel YE, Brummer RJ, Kippeschaar HP. Deuterium and broimde dilution, and bioimpedance spectrometry independently show that growth hormone-deficient adults have an enlarged extracellular water compartment related to intracellular water. *J Clin Endocrinol Metab*. 1997;82:907–11.
34. Wang Z, Deurenberg P, Wang W, Pietrobelli A, Baumgartner RN, Heymsfield SB. Hydration of fat-free body mass: review and critique of a classic body composition constant. *Am J Clin Nutr*. 1999;69:833–41.
35. Wilmore JH, Vodak PA, Parr RP, et al. Further simplification of a method for determination of residual lung volume. *Med Sci Sports Exerc*. 1980;12(3):216–18.

BASIC SCIENCES