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RESEARCH ARTICLE

Uncovering the FUTREX-6100XL prediction equation for the percentage body fat

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Based on the near infra-red (NIR) interactance method, the FUTREX company has developed a series of instruments, for the estimation of the body fat percentage (%BF). %BF is estimated through prediction equations incorporated in the instruments, which for the newest models (FUTREX-6100XL and FUTREX-6100A/ZL) are proprietary and they are not published anywhere. This missing knowledge may lead to several misunderstandings and confusion and degrades those instruments to 'black boxes'. The present work uncovers and presents the prediction equation of FUTREX-6100/XL and discusses the contribution of each term of that equation to the %BF. Furthermore, this study presents the method used, which can be used to uncover equations incorporated in other instruments. This method is based on the idea of firstly uncovering the dependence of the equation on each parameter separately and then combining those dependencies to uncover the unknown equation.

Keywords: Body composition, FUTREX, Near infra-red interactance, Prediction equation, Body fat

Introduction

Two decades ago, the known field methods for estimating the body fat percentage (%BF) were the skin-fold (SKF) [1] method and the bioelectric impedance analysis (BIA) [2]. Over the last two decades a new field method has been proposed for estimating the %BF, which is the so-called near infra-red (NIR) interactance method [3].

NIR interactance method is based on the absorption of the NIR light from the BF and the body water. Conway *et al.* [4] reported that two different absorption peaks appear for water and fat, at 970 nm and 930 nm, respectively, and that the shape of the absorption profile at those wavelengths is related to the amount of fat and water of the human tissue being measured. Based on this, FUTREX company developed an instrument–device which measures the optical density (i.e. the absorbance) at selective NIR wavelengths, as light travels from the skin through the biceps to the bone and back.

The NIR interactance method is more convenient compared to the BIA and SKF methods. For example, according to the protocol of the BIA method, the patient must not have eaten any food for the last 12 h and must not have drunk any alcohol for the last 24 h before the measurement [3]. According to the protocols of the SKF method, skin-folds have to be measured at several places of the body, for some of which the patient has to be undressed. Since those measurements have low reproducibility, many measurements must be taken in order to achieve an acceptable estimation, which makes the method time-consuming. In addition, SKF measurements must be taken by someone who has the skills. Otherwise there is a high possibility that the measurements will be wrong. On the other hand, the NIR interactance method is easy, fast, without special restrictions for the patient, its estimations are reproducible and measurements can easily be taken, even by inexperienced personnel. Consequently, the NIR method is very useful for day-by-day clinical work. Furthermore, its high reproducibility [3] makes it a very useful method for recording credible changes in %BF.

In order to estimate the %BF values, the optical densities (ODs) at specific NIR wavelengths are recorded, while other parameters such as *Height*, *Weight*, *Age* and *Sex* are also taken into account.

The first FUTREX model, FUTREX-5000, measured the optical densities (ODs) at two wavelengths (940 nm and 950 nm) and used an equation of the form

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$$\%BF = 58.0 - 26.3(OD_2 - \Delta OD_2^s) - 4.7\ (OD_1 - \Delta OD_1^s) + 0.104(Weight) - 5.31(Height) - 2.478(Sex) - 1.366(Exercise\ Level) \quad (1)$$

where OD_1 and OD_2 are the optical densities at 940 and 950 nm, respectively, ΔOD_1^s and ΔOD_2^s are the differences of the optical densities of a standard optical material between the manufacturer's calibration and the calibration performed by the operator before the measurement, *Sex* takes the values 1 for males and −1 for females, the *Weight* and *Height* are measured in kg and m, respectively, and the *Exercise Level* takes one of the values 0, 2, 5 or 8 depending on the exercise level [5]. FUTREX-5000 has been widely used in the last two decades by many research groups [3,5–11]. However, it was reported that its results were not accurate enough [9–11].

To improve the accuracy of the BF estimations, Futrex company introduced a new series of models (FUTREX-6100XL and FUTREX-6100A/ZL). The difference between these two models is that FUTREX-6100XL can be used only for adults, while FUTREX-6100A/ZL can also be used for adolescents and children. The new models measure the optical density (OD) at the wavelengths 810, 932, 944 and 976 nm (instead of 940 and 950 nm on the 5000-series). Those wavelengths were probably found to be more appropriate for the %BF estimations by the manufacturers. In addition, FUTREX-6100XL and FUTREX-6100A/ZL use different prediction equations for the estimations of %BF for adults, adolescents and children and they have the ability to measure the ODs at 910 and 1023 nm, although these wavelengths are not used in the prediction equations. The wavelengths for which the ODs are used in each one of those equations are [12]: 810 and 944 nm for adults (used by FUTREX-6100XL and FUTREX-6100A/ZL), 944 and 976 nm for adolescents (used only by FUTREX-6100A/ZL) and 932 and 944 nm for children (also used only by FUTREX-6100A/ZL). However, the prediction equations incorporated in these new models are proprietary by the FUTREX company and have not been published anywhere [12].

In addition, very few papers (see for example the works of Fthenakis *et al.* [13] and Zafiropulos *et al.* [14]) have reported the use of those new models in relevant research, although the manufacturers claimed that their new models have been improved compared to their previous ones. In some cases this is due to the absence of any knowledge on the prediction equations incorporated in those models, which makes them not very attractive for research purposes, except if someone is satisfied using those devices as 'black boxes', which can give estimations of the %BF, no mater how those estimations were produced. On the other hand, if someone wants (a) to test the estimations of the FUTREX-6100 series models, (b) to understand how these instruments estimate the %BF, (c) to use them for further research purposes beyond the estimations of the %BF under the conditions of their certain protocol and/or (d) to improve the quality of the predictions, then he/she would be interested to know the form of the prediction equations used by the manufacturers. Additionally, the knowledge of the %BF prediction equation would be helpful for the production of an accurate prediction equation for %BF changes and assessing dietary interventions, since measurements with FUTREX-6100XL on the same person show high reproducibility and consequently small differences of the %BF are expected to be accurately estimated.

Furthermore, the absence of papers on (or with the use of) FUTREX-6100 model series and the missing knowledge on their prediction equations leads to confusion and misunderstandings. Many people believe that FUTREX-6100 series models use the optical densities of six wavelengths instead of two [15] and they might also think that this is the reason why FUTREX-6100 series models are more accurate than the FUTREX-5000. Others think that the prediction equations of the FUTREX-6100 series have more or less the same form with the one used by the FUTREX-5000 series. For example, in their paper, Kalantar-Zadeh *et al.* [16] thought that the form of the %BF prediction equation, which is used by the FUTREX-6100XL instrument, has the form

$$\%BF = K_0 + K_1 \times (OD_1) + K_2 \times (OD_2) + K_3 \times (Height) + K_4 \times (Weight) + K_5 \times (Age) + K_6 \times (Sex), \quad (2)$$

where $K_0, K_1, \ldots, K_6$ are constants and OD_1 and OD_2 are the optical densities of the two specific wavelengths. However, this is not the correct form of the prediction equation used by the manufacturers, as will be shown in the present paper.

To avoid all this confusion, to give answers to practitioners who are interested in the form of the FUTREX-6100XL prediction equation for the %BF, to improve this equation and for all other purposes presented above, the prediction equation of the FUTREX-6100XL model is uncovered and presented in this paper.

The method

For convenience let us call OD_1, OD_2, OD_3 and OD_4 the optical densities at the wavelengths 810, 932, 944 and 976 nm, respectively, which are measured and used by the FUTREX-6100XL instrument. We tried to uncover the form of that equation by keeping the parameters that affect the measurement (i.e. OD_1, OD_3, *Height*, *Weight*, *Age*, *Sex*) constant, except for one at a time, and see how the estimations of %BF change with the varied parameter. This is the usual way to find the dependence of the prediction equation on the parameter that varies. The form of the equation can be depicted by applying the least squares fitting method on the data. Then the procedure is repeated for the rest of the parameters, one parameter at a time.

However, following the previous mentioned methodology, a minor difficulty appears, owing to the fact that it was not possible to keep constant the values of the OD_1, OD_2, OD_3 and OD_4 parameters separately. To overcome this problem, measurements were taken on the same person. Thus, the four OD values were almost constant, with small insignificant changes from one measurement to another owing to random errors.

Results and discussion

Uncovering the %BF prediction equation

For the moment let us assume that the form of the %BF equation is

$$\%BF = f(OD_1, OD_3) + g(Height, Weight, Age, Sex) \quad (3)$$

where *f* is a function of only the optical densities OD_1 and OD_3 and *g* is a function of all the other parameters. As it will be shown at the end, this assumption is correct.

Taking measurements with the FUTREX-6100XL on the same person, the function $f(OD_1,OD_3)$ of the above equation can be treated as an unknown constant and not as a complicated function, as explained previously. However, if we speak with exactitude, we should say that, under the conditions of repeated measurements on the same subject, the values of the *f* function insignificantly vary owing to random errors, which can be treated with the least square fitting method. In this case, using the *f* function as a constant we can write

$$\%BF = g(Height, Weight, Age, Sex) + \text{constant}. \quad (4)$$

Based on equation (4) and by varying one of its parameters at a time (i.e. Height, Weight, Age and Sex), the form of the %BF prediction equation of the FUTREX-6100XL was uncovered.

%BF vs Age

First we found how the values of %BF vary as a function of *Age*. The other parameters except Age were given the values: *Weight* = 65 kg, *Height* = 1.70 m and *Sex* = Female. We gradually changed the values of *Age* from 18 years to 100. According to the manual accompanying FUTREX-6100XL, the minimum entry value of the parameter Age that is accepted by the particular model is eighteen. The values of the %BF calculated by FUTREX-6100XL vs age are depicted in Figure 1. As one can see, the prediction equation of the FUTREX-6100XL shows a linear dependence of %BF on *Age*. The equation derived via the linear least square fitting procedure is

$$\%BF = 0.146 \times (Age) + 20.884 \quad (5)$$

with a value of $r^2 = 0.9895$. A quadratic or a higher power least square fitting does not give any significant changes which would make these forms preferable. For example, the quadratic form obtained from the least square fitting method is $\%BF = -5\times10^{-5}(Age)^2 + 0.1523\times(Age) - 20.732$, with $r^2 = 0.9986$.

%BF vs Weight

Next, the values of *Age*, *Height* and *Sex* were fixed at 18 years, 1.70 m and *female*, respectively, and the parameter of the *Weight* was gradually changed from 30–225 kg. The %BF values obtained with the FUTREX-6100XL are shown in Figure 2. As one can see, the %BF is also linear with the Weight, in the region 30–120 kg, but it is constant for *Weight* > 120 kg.

For the interval of 30–120 kg a least square fitting procedure predicts a dependence of the form

$$\%BF = 0.3824 \times (Weight) - 1.3939, \quad (6)$$

with a value of $r^2 = 0.9978$. As in the previous case, a quadratic or a higher power fitting does not give any significant differences, which would make these forms preferable. The corresponding quadratic form is $\%BF = 2 \times 10^{-4} \times (Weight)^2 + 0.3494 \times (Weight) - 0.3467$, with $r^2 = 0.9980$.

For *Weight* > 120 kg the least square fitting method gives a linear dependence of the form $\%BF = 0.0023 \times (Weight) + 45.114$ with $r^2 = 0.1037$. This indicates that, in this case, there is not any strong correlation between the %BF values and the values of the *Weight* and, therefore, %BF is independent of the *Weight* for *Weight* > 120 kg. As we will show later, FUTREX-6100XL can not estimate the %BF values if they exceed the value of ~ 45. In these cases it returns a value of ~ 45 and this is what we observed in our measurements for *Weight* > 120 kg, trying to find the %BF dependence on *Weight*.

%BF vs Height

Trying to find the dependence of the %BF on the *Height*, the parameters of *Weight*, *Age* and *Sex* were fixed to the values 70 kg, 18 years and *Female*, respectively. The values of the *Height* were gradually changed from 1.25–2.25 m. Figure 3 shows the dependence of the %BF on *Height*. What one can see is that the trend of those points does not correspond

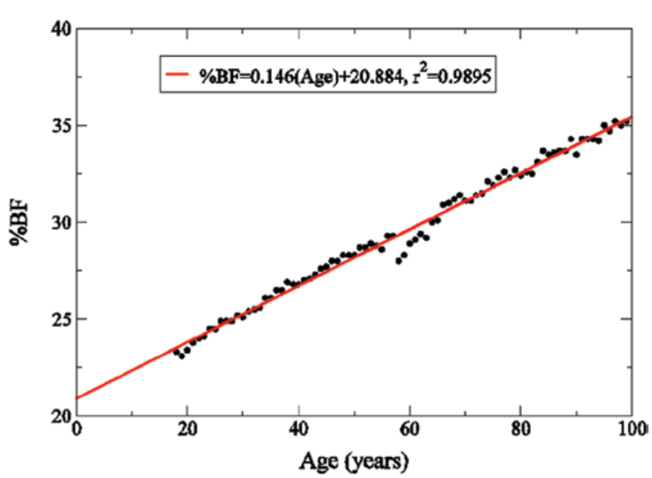

Figure 1. %BF vs *Age*.

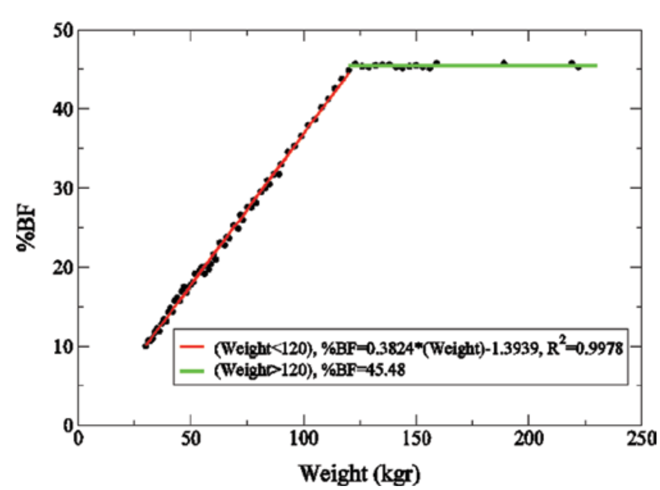

Figure 2. %BF vs *Weight*.

to a straight line. However, if we plot the %BF against $1/(Height)^2$, the figure of a straight line appears (see the inset of Figure 3). The equation derived via the linear least square fitting procedure is

$$\%BF = 75.09 \times \frac{1}{(Height)^2} - 0.7873, \tag{7}$$

with a value of $r^2 = 0.9971$. This lead us to conclude that a $1/(Height)^2$ is a possible form of the dependence of %BF on the *Height* and made us suspect a BMI (= $Weight/(Height)^2$) dependence of the %BF, rather than a $1/(Height)^2$ and a linear dependence on *Weight* separately in two solely additive terms. This suspicion became stronger when we realized that, if we divide the slope of the straight line of the inset of Figure 3 with the constant value of the *Weight*, we found: 75.09/70 = 1.072. Also, if we multiply the slope of the straight line of Figure 2 with the square of the constant value of the *Height* we found: $0.3824 \times (1.70^2) = 1.105$. Those two values (1.072 and 1.105) are very close to each other, and they would represent the slope of a straight line of %BF vs BMI.

Finally, what we observed in Figure 3 was that for small values of Height, (*Height* < 1.30 m), for which equation (7) predicts %BF values larger than ~45, the %BF values obtained by the instrument do not follow the predictions of equation (7), but they rather remain almost constant, in accordance with what we noticed before, that FUTREX-6100XL can not estimate the %BF values if they exceed the value of ~45.

%BF vs BMI

To ensure that we have to do with the BMI and not with the *Height* and the *Weight* separately, we used the results already obtained from the previous measurements and also another set of measurements of the %BF for another person for which the values of *Age* and *Sex* were 18 years and Male, respectively, and we plotted the graph of the %BF against BMI. What we find is depicted in Figure 4.

As one can see in this Figure, the values of the %BF rise linearly with the BMI until the %BF reaches the value of ~ 45.4. For larger values of BMI, the predicted values of %BF remain almost constant, ranging between 45.0–45.9.

In addition, taking measurements on different people, for which the OD values were different between each other, we found that, if the values of the %BF obtained by the instrument reach the value of ~45.4, then the %BF values seems to be independent not only of the BMI, but also of the OD values and they seem to be randomly distributed in the range 45.0–45.9. This indicates that FUTREX-6100XL can not estimate the %BF values if they exceed the value of ~45, as we have already mentioned. On the other hand, the distribution of those %BF values in the range of 45.0–45.9 was something unexpected and difficult to rationalize.

%BF vs Sex

As one can see from Figure 4, the difference between %BF measurements for males and %BF measurements for females is a constant value. This means that the %BF dependence on *Sex* is just an additive term, which can be determined according to the values we assign to the parameter *Sex*. For instance, if *Sex* = 1 for males and 0 for females, the term $C \times (Sex)$, with $C \approx -10.4$, has to be inserted in the prediction equation. The same conclusion would arise, using the method used above to find the dependence of *%BF* on *Age*, *Weight* and *Height*.

The %BF dependence on ODs and the %BF prediction equation

What we have found so far, is that if $\%BF = f + g$ (see equation 3), then

$$\%\text{BF} = \begin{cases} f(ODs) + g, & \text{if } f + g < 45 \\ 45.4 \pm 0.5, & \text{if } f + g > 45, \end{cases} \tag{8}$$

with *g* having the general form

$$g = A \times (BMI) + B \times (Age) + C \times (Sex). \tag{9}$$

In this equation $A \approx 1.1$, $B \approx 0.146$, $C \approx -10.4$, *Sex* = 1 for males and 0 for females, BMI is in kg m^{-2} and *Age* in years.

As mentioned above, technically it is not easy to get %BF measurements, keeping all the parameters constant except

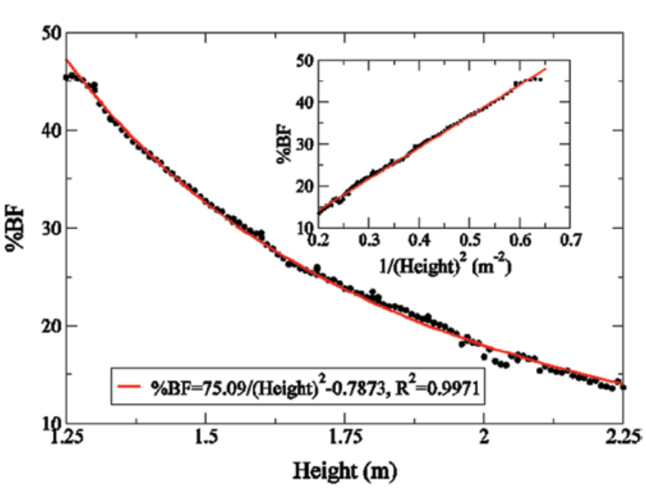

Figure 3. %BF vus *Height*.

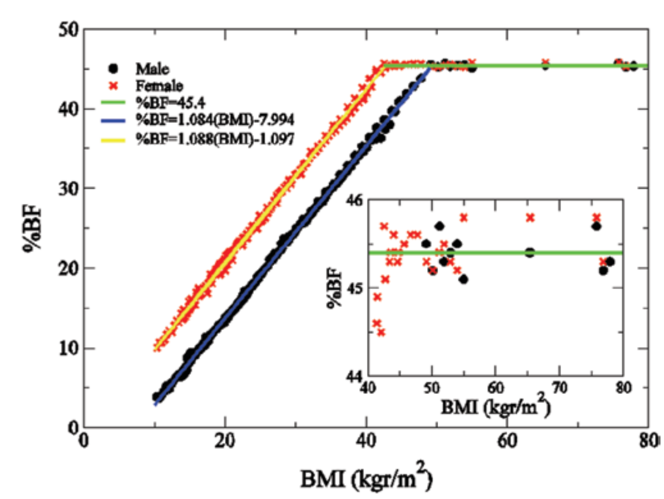

Figure 4. %BF vs BMI obtained from two different persons.

one of the ODs. Therefore, we can not find the dependence of the %BF on each OD separately, as we did with the parameters *Age*, *Sex* and *BMI*. Thus, what we will try to do is to find the %BF dependence on all the ODs, simultaneously. In the next few paragraphs we explain how we will do this.

If our assumption that $\%BF = f + g$ is correct, then what remains to be done is to find the general form of *f* and determine its coefficients. Let us assume that we know the general form of *f*, but we don't know its coefficients. If the number of those coefficients is *n*, then getting measurements of %BF with the FUTREX-6100XL for *n* independent sets of values of the equation parameters, we can determine the unknown coefficients by solving the $n \times n$ system of equations which will arise. If our assumption for the form of the prediction equation is correct, then the %BF measurements for any set of parameter values will be exactly the same with the corresponding %BF values obtained by the proposed equation and the proposed equation is the prediction equation of the instrument.

On the other hand, the determination of the coefficients and the validation of the form of the equation can be done simultaneously, using the least squares fitting method. What we have to do is to get %BF measurements using FUTREX-6100XL for a very large sample of parameter values, no matter if those measurements are true measurements of the %BF of individuals. Using the least squares fitting method to fit those %BF values to the proposed general form of equation, we will obtain the values of its coefficients. This equation will be the prediction equation of the instrument, if all the %BF measurements are equal to the corresponding %BF values obtained by the equation, despite some negligible differences of minor interest, which might appear due to truncation errors.

Following this methodology, we assume a linear dependence of the %BF on OD_1 and OD_3, which, according to the manufacturers, are the two OD parameters used by the FUTREX-6100XL. Thus, the prediction equation is assumed to have the general form

$$\%BF = a_0 + a_1 \times OD_1 + a_3 \times OD_3 + A \times (BMI) + B \times (Age) + C \times (Sex). \quad (10)$$

Using the least squares fitting method, as implemented by the Origin suite [17], we determined the coefficients a_0, a_1, a_3, A, B and C. Nine hundred and seventy-eight %BF measurements obtained by the FUTREX-6100XL instrument for their corresponding 978 sets of parameter values were used for the fitting. Those sets of parameter values were selected so that they cover all the space of their possible values. The values of the coefficients found are: $a_0 = -8.640 \pm 0.012$, $a_1 = -1.142 \pm 0.062$, $a_3 = -20.77 \pm 0.07$, $A = 1.093 \pm 0$, $B = 0.145 \pm 0$ and $C = -10.426 \pm 0.005$. Zero error of the above values means that the error is less significant than the most significant figure of the corresponding value. What remains to be done is to verify that the values obtained by the above equation are the same as those measured by the instrument, and this is what we will show next.

Once more, we notice that this equation is valid only for adults (i.e. for ages > 18 years) and that the prediction equations for adolescents and children are different.

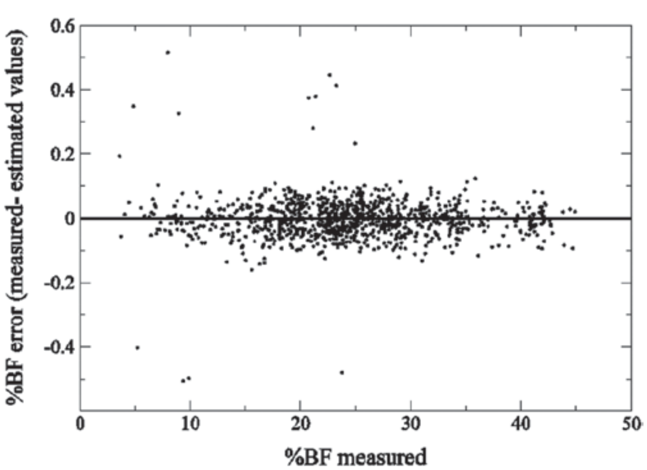

Figure 5. The differences between the estimated values (from equation 10) and the measured values (from the instrument) of the %BF, vs the measured values of %BF.

Verification

In Figure 5 we present the difference between the %BF values obtained from equation (10) and the measured values from the instrument vs the measured values of %BF. The vast majority of those differences (973 out of 978) range between −0.1 and 0.1 and only 41 of them range (in absolute value) between 0.1–0.5.

Absolute differences of less than 0.1 can be understood in terms of truncation errors, because 0.1 is the reading error of the instrument. Absolute differences between 0.1–0.5 can be understood in terms of propagating errors. Recall, however, that differences of that order also occurred between the extreme values of %BF ($\%BF \approx 45 - 46$, see inset of Figure 4), which were supposed to be constant and independent of the *OD* values.

In addition, the distribution of the differences (in absolute value) of Figure 5, which is presented in Figure 6, looks like a Gaussian distribution.

This makes us suspect that, despite the possibility that errors of the order of 0.1 up to 0.5 are propagating errors, a possible source of those differences might be a random number generator incorporated in the instrument by the manufacturers, in order to make any attempt at uncovering the equation a difficult task.

In conclusion, we successfully verified that equation (10) is the prediction equation used by the FUTREX-6100/XL for the %BF estimations.

Contribution of each term of the equation to the %BF estimations

Table 1 shows the minimum and the maximum values of each one of the parameters which affects the %BF and the minimum and maximum value of the respective term of the equation. The values −0.6 and 0, presented in that table for the minimum and maximum values of the ODs, respectively,

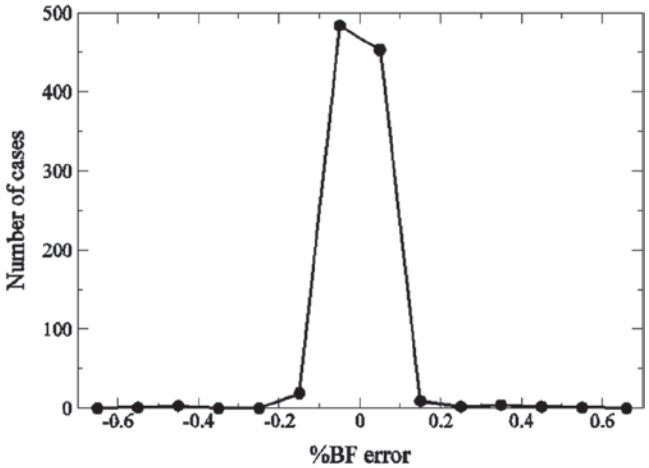

Figure 6. The distribution of cases vs the error of %BF (i.e. %BF estimated (by the equation) – %BF measured (by the instrument)).

Table 1. (a) The minimum and the maximum value of the parameters of the prediction equation for the %BF, (b) the minimum, the maximum and the average value of the terms of the prediction equation.

Variable	Min value	Max value	Term	Min value	Max value	Average value
OD_1	−0.6	0	$a_1 \times (OD_1)$	0.0	0.7	0.4
OD_3	−0.6	0	$a_3 \times (OD_3)$	0.0	12.5	7
BMI	6	50	$A \times BMI$	6.6	54.0	24
Age	20	100	$B \times Age$	2.9	14.5	8.7
Sex			$C \times Sex$			−10.4 or 0
Constant			a_0			−8.6
			%BF			≈ 20 or 30

are the minimum and maximum values we found after taking hundreds of measurements with FUTREX-6100/XL on individuals. The last column of Table 1 shows the average value of each one of those terms. For those average values, the %BF takes the value of ~20 for males and 30 for females.

As one can see from this table, the contribution of the OD_1 is minor. The prediction equation for the %BF seems to be very sensitive on BMI and OD_3 (i.e. small changes in these two parameters leads to large changes in %BF), while the prediction equation is not so sensitive in OD_1 and *Age*. For instance, if the error on *Age* is 1 year (maximum possible error), the error on %BF will be less than 0.15. The error from the OD_1 (no mater what its value is) can not exceed the value of 0.4. The term $C \times (Sex)$ is an additive term without any error.

According to the uncovered equation, between two individuals with the same *Sex*, *Age* and *BMI*, the value of OD_3 will be smaller for the one with the higher %BF. This means that OD_3 estimates the absorbance of water and not the absorbance of the fat. It is worth noting that the wavelength corresponding to OD_3 is $\lambda = 944$ nm, which is almost in the middle of the wavelengths $\lambda = 930$ nm and $\lambda = 970$ nm, corresponding to the absorption peaks of fat and water, respectively.

Bearing in mind that the values of the parameters *Sex* and *Age* are the same for all individuals of the same age and sex, the FUTREX-6100XL %BF measurements depend mainly on BMI and OD_3. This conclusion, somehow, falls short of our expectations. We wouldn't expect an instrument like FUTREX, which incorporates the NIR technology and is based on the very reasonable considerations of the NIR interactance method, to estimate %BF using quantities like BMI, which can only roughly estimate the BF situation. Of course, BMI itself is not a very bad predictor of %BF. However, it is not evident why BMI should be incorporated in a NIR interactance prediction equation for the %BF. In addition, the prediction equation is linear on the ODs, which of course is the simplest form of an equation; however, considering the laws of light absorption, it is not easy to rationalize why this equation has to be linear. In other words, one would rather expect a more sophisticated prediction equation, which would not include any anthropometric measurements and will be based only (or mainly) on some reasonable considerations of the NIR interactance method.

Conclusion

Using the method described above, which is a general method to uncover unknown prediction equations, the FUTREX-6100XL prediction equation for the %BF (equation 10) has been uncovered. Despite some small differences owed to truncation errors, it has been found that the %BF values obtained by the uncovered prediction equation are the same with those measured by the instrument. This is evidence that equation (10) is the equation used by the FUTREX-6100XL.

For large values of %BF (%BF > 45), the FUTREX-6100XL %BF estimations lay between the values 45–46, no matter what the OD values or the values of the other variables are. Therefore, for such large values of %BF, the FUTREX-6100XL instrument is not proper for estimations of the %BF. The prediction equation of FUTREX-6100XL for the %BF is based mainly on BMI and the OD at the wavelength $\lambda = 944$ nm. This OD acts as an estimator of the absorbance of NIR from the water of the tissues.

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