

Original Article

A digital Calliper for training and study purposes

Maria T Restivo PhD¹, Teresa F Amaral PhD^{1,2}, Maria F Chouzal PhD¹, Celina P Leão PhD³, Rita S Guerra MSc^{1,2}, Elisa Marques PhD⁴, Joaquim Mendes PhD¹, Manuel Quintas PhD¹, Jorge Mota PhD⁴

¹UISPA-IDMEC Campus FEUP, Faculty of Engineering, University of Porto, Rua Dr Roberto Frias, 4200-465 Porto, Portugal

²Faculty of Nutrition and Food Sciences, University of Porto, Rua Dr Roberto Frias, 4200-465 Porto, Portugal

³Scholl of Engineering, University of Minho, Campus de Azurém, Portugal

⁴Research Centre in Physical Activity, Health and Leisure, Faculty of Sport Sciences, University of Porto, Rua Dr Plácido Costa 91, 4200-450 Porto, Portugal

A quick and valid method for evaluating percentage body fat is based on the use of skinfold callipers. However, limitations associated to their use and characteristics led the authors to improve a traditional calliper (Harpender) and to integrate it with a software application. Such a measuring system, LipoTool, is meant to have better accuracy and reliability, including data processing and digital recording at a very low cost. At first, a sample of 49 older adults was used to evaluate the performance of LipoTool by comparing its results to those obtained with the traditional Harpenden calliper. A strong positive association in %BF was achieved. This digital sensing system was later improved by incorporating wireless communication between the calliper and the software application, adding other functionalities. The software application works in any computer and is flexible to incorporate new coming models, linear regressions or new algorithms. This new system was validated against the standard Dual-Energy X-Ray Absorptiometry system, using a sample of 40 adults with positive results. This solution is a valid and reliable alternative to traditional reference callipers, simplifying the percentage of body fat evaluation and providing a more effective use in daily practice with less expenditure of time and resources. Its implemented guided procedure turns it into a precious training tool based on a non-invasive, portable device, and not requiring special individual preparation. Ongoing activities are focused on the design of a new mechanical structure, with novel functionalities and for exploring other studies.

Key Words: body fat percentage, digital skinfold calliper, training system, wireless data communication, automated process

INTRODUCTION

Individual changes in nutritional status are the most common health problem with high impact in society at individual, social and economic levels. Malnutrition, obesity or even the co-existence of both is a major world health problem.

The nutritional problems affecting industrialized countries are related with high energy food intake, leading to overweight, obesity and associated co-morbidities.

The assessment of percentage body fat (%BF) is highly relevant for the evaluation of nutritional status, growth and childhood development, disease impact and sports practice.¹

Different methods are available for evaluating malnutrition and obesity. The Dual-Energy X-Ray Absorptiometry (DXA) method is one of the most widely applied techniques for %BF studies.² This method, as others based on imaging, relies in very expensive, bulky and invasive equipment unsuitable for daily diagnosis.¹

A widespread method, simple and non invasive, for evaluating subcutaneous fat tissue is based on the use of

low cost and portable equipment, such as the skinfold calliper (SC),^{3,4} which allows for quantitative indirect evaluation of fat tissue by measuring skinfolds. The SC provides a validated diagnostic method, using skinfold measurement for evaluating %BF,¹ based on the two compartment model which divides the body into fat mass and fat-free mass.

Nevertheless, SC measurements have to be performed by highly trained health technicians following standard procedures^{5,6} in order to minimize subjective decisions and individual variability.

All different types of SC accepted as valid devices in the nutritional area present limitations, making them unat-

Corresponding Author: Dr Maria T Restivo, UISPA-IDMEC Campus FEUP, Faculty of Engineering, University of Porto, Rua Dr Roberto Frias, 4200-465 Porto, Portugal .
Tel: +351225081701, +351913503009; Fax: +351222074241
Email: trestivo@fe.up.pt
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Figure 1. LipoTool with a Harpenden SC adapted with a digital dial indicator.

tractive and so less used in daily practice.

In fact, the needle movement around the analogue display during tests, due to tissue yield under pressure, makes the measurement difficult and leads to subjective readings. Also, it is highly subjective to mental counting (2, 3 or 4 seconds) once the calliper jaws touches the fold surfaces and then the jaws pressure is slowly released.⁷

Manual data registration means time consumption or even requires a second technician responsible for registering data. The oral transmission process of the measured data is also subject to errors. Finally, the natural interaction with the individual under assessment influences the subjective mental evaluation of the time interval and the visual readout of the rotating needle.

To assess body density and %BF, regression equations are required after the skinfold thickness measurement. There are many equations, developed for different ages, gender, races or specific groups, requiring the selection of the most appropriate, based on its validity within the population under study. These calculations are an additional task making the assessment of %BF even more difficult and time consuming.

Those problems and the need to improve measurement accuracy, reliability, data processing and digital recording, using today's technology, have led to the development of a new solution for %BF assessment based on the skinfold thickness measurement, the LipoTool, comprising a modified SC, Adipsmeter, and a LabVIEW software application, LipoSoft.

The Adipsmeter is based on a Harpenden calliper, recognized in the specialized literature,^{3,5,6,8,9} mechanically adapted and electronically instrumented with a digital dial indicator. A data communication interface allows the calliper communication with a software application offering a user-friendly interface. The application developed for monitoring, digital recording and assessing body composition may also integrate a database. A second iteration of the system incorporates digital sensing and a wireless communication system with the software application.

The digital sensing accurate system significantly reduces evaluation subjectivity and considerably increases checking task efficiency, making it an excellent training tool. The features of the system prototype make it a precious tool for training nutritional technicians, trainees for research work and for field use in large population studies due to its recording capabilities in database.

MATERIAL AND METHODS

LipoTool system

The material to be described in this work is an integrated system named LipoTool. It consists of an adapted Harpenden skinfold calliper, Adipsmeter, and a software application, LipoSoft, for monitoring, measuring and recording subcutaneous fat tissue in a systematic, accurate and expeditious way. The Harpenden is used because it is a benchmark SC recommended by the International Society for the Advancement of Kinanthropometry (ISAK).⁸

In the first version the digital developed system incorporates a Harpenden calliper mechanically adapted for allowing the automatic skinfold thickness measurement, by replacing the analogue dial indicator by a digital one. It communicates with the PC software application through a cable interface (Figure 1).¹⁰

Digital information eliminates reading errors that might happen when measuring with a rotating needle moving around the analogue scale, as in the original Harpenden. The needle movement has not constant speed, varying according to the body tissues composition. This makes measurement difficult during the measuring time interval of 2 to 4 seconds, selected in the software application, after pressuring the tissue, according to established procedure. The counting time, the needle position readout and its manual registration, all traditionally subjectively performed by the technician, are now done digitally and automatically.

Two miniature switches have been added to the calliper to allow user interactivity with the computer application.

The software application has been developed in LabVIEW and presents a user-friendly graphical interface. It offers an intuitive guidance through the established procedure for %BF assessment, avoiding subjective measurement and calculation errors – mentally counting the protocol time interval and reading the position of the moving needle in an analogue display. A visual graphical evaluation of the measurement is monitored. The %BF value is available after performing the skinfold thickness measurement and according to the selected equations from the specialized literature offered by the software.^{6,8} It also integrates a database allowing individual data recording and updating. This application has six sequential levels: entry, individual search, new individual identification, individual data update, measurement and processing data panels, through the selection of equations for body composition determination.



Figure 2. LipoTool integrating sensing and wireless communication system.

At the individual search level the LipoSoft application looks for the personal details in the database, according to the individual process number introduced. If no information is found, the application switches to the new individual identification panel. If the individual is already registered, the update panel opens and new tests are performed according to the selected method. If measurements are not adjusted to the selected method, the technician is informed and the application automatically redirects her/him to the adequate menu level. The LipoSoft notably reduces evaluation subjectivity, increases the efficiency and is easily updatable.

However, negative aspects were outlined: the solution is heavier than the traditional calliper and the interface cable causes handling unbalance. A new iteration tries to overcome those features, looking for a new digital, miniaturized, light and low cost sensing system. In parallel, the new prototype should integrate a wireless data transmission solution for the computer (Figure 2), making the system easy to use in daily clinical practice and in large population samples.

The digital dial indicator incorporated in the calliper was replaced by a miniaturized encoder, ensuring a contactless skinfold thickness measurement and lowering maintenance costs. This provides the device with a resolution (0.35mm) three times better than that typically required by these systems (better than 1mm). The new final prototype weighs less than the original Harpenden.

To overcome undesired effects from the data transmission cable (causing important interference with the individual position relatively to the computer and introducing unbalance in the technician manipulation) the ZigBee technology was used for the wireless communication system. The wireless receiver is connected to a USB computer input. A rechargeable battery is incorporated for powering the system with 9h autonomy, through USB/USB, car battery, USB/220V A.C. connections, flexible for field use.

The LipoSoft application was then adapted to the wireless data communication protocol requirements, named LipoSoft ZigBee. This new application has also other structural improvements. The access to the individual graphical history record for tracking the evolution of his/her body composition has been added.

At the data processing level, other features were introduced. So, according to the selected method, the technician will be notified if any type of skinfold measurement has not been carried out, indicating which ones should additionally be measured. According to individual history, his/her %BF maximum values, a first analysis of the present result is possible, even for a less experienced technician. At the end of the tests a printed report is produced. For safeguarding data an "encrypt" function was created.

Performance evaluation

The performance of the first version of LipoTool was evaluated through a cross-sectional study using a sample of 49 elderly Caucasian subjects, aged from 61 to 92 years, on a voluntary bases. This study was conducted in accordance with the internationally agreed ethical principles for the conduct of medical research (Declaration of Helsinki). All the participants were informed of the study purposes as well as the different procedures. Verbal informed consent from all the subjects was witnessed and formally recorded. This elderly group reports participating in some kind of physical exercise, at least twice a week: 37%, 41%, 12% and 10% respectively two, three, four and five or more times per week.

The %BF was estimated based on skinfold measurements performed by the original Harpenden, used as the test reference, and with the Adipmeter. Both callipers were pre-calibrated.

The height and weight were measured according to techniques and procedures described in the literature.¹¹ Height was measured, with subjects standing barefoot, with a stadiometer (Seca 708 model and resolution of 0.01 m). The weight was measured with a scale of 0.5 kg of resolution with subjects wearing underwear and an exam gown. The BMI was then estimated using these two characteristics, $BMI = \text{weight (kg)} / (\text{height (m)})^2$.

The measurement of skinfold in the triceps, biceps, subscapular and iliocristale parts of the human body were made on the right side and in triplicate,⁹ with both callipers, by an Anthropometrist accredited by ISAK. Body density and %BF were estimated using the mean of the three measured values for each calliper. Body density was estimated using the equations of Visser *et al.*¹² and %BF was estimated using the equation of Brozek *et al.*¹³ The mean %BF was estimated based on Harpenden measurements and from LipoTool results.

The total error (TE) was calculated as:

$$TE = \sqrt{\sum (y_H - y_L)^2 / n}$$

where y_H are the estimated values based on Harpenden measurements and y_L are the values coming from LipoTool.

Table 1. Characterization of the two samples used (1: elderly people and 2: adults samples) (mean±sd[†])

	Females		Males		Total	
	(n ₁ =34)	(n ₂ =25)	(n ₁ =15)	(n ₂ =15)	(n ₁ =49)	(n ₂ =40)
Age (years)	72.9±5.57	40.9±11.5	70.4±4.09	24.7±2.9	72.1±5.25	34.8±12.1
Height (m)	1.53±0.06	1.58±0.05	1.68±0.05	1.77±0.05	1.58±0.09	1.65±0.11
Weight (kg)	61.4±7.17	58.3±9.4	75.1±7.77	78.4±12.5	65.6±9.68	65.9±14.4
BMI (kg/m ²)	26.3±3.44	23.4±3.7	26.6±2.18	25.1±4.1	26.4±3.09	24.0±3.9

[†] Sd-Standard deviation

Table 2. Association between %BF estimated by the LipoTool and by the Harpenden - elderly sample.

	Mean±sd	<i>r</i>	<i>r</i> ²	Intercept	Slope	<i>s_x</i> [†]	TE [‡]
Total (n=49)							
Harpenden	38.0±5.85	0.997*	0.994	0.190**	0.993*	0.458	0.46
LipoTool	37.9±5.83						
Harpenden-LipoTool	0.082±0.46						
Females (n=34)							
Harpenden	41.7±1.83	0.969*	0.939	-2.60**	1.06*	0.502	0.36
LipoTool	41.5±2.00						
Harpenden-LipoTool	0.127±0.51						
Males (n=15)							
Harpenden	29.6±1.13	0.967*	0.935	-0.386**	1.01*	0.314	0.29
LipoTool	29.6±1.19						
Harpenden-LipoTool	-0.021±0.30						

[†] *s_x*, Standard error estimation; [‡]TE, Total error; **p* < 0.01; ***p* > 0.05.

The correlation coefficient, *r*, was used to evaluate the association between the values of %BF estimated by the two systems. To describe the agreement between the measurements obtained by both callipers, a Bland-Altman plot was done.¹⁴

In a second stage, the performance of the new integrated system LipoTool incorporating a wireless communication protocol was also tested with a sample of 40 Caucasian adults aged from 22 to 58 years. This study was conducted in accordance with the internationally agreed ethical principles for the conduct of medical research (Declaration of Helsinki).

Most adults declared practicing some form of physical exercise (72.5%, being 45% men and 27.5% women) distributed as follows: 27.5%, 10%, 10% and 25% respectively two, three, four and five or more times per week.

The %BF was estimated with the original Harpenden and the LipoTool. Both callipers were previously calibrated. These measurements were performed and compared with parallel DXA measurements, as a gold standard system. The height and weight were measured and BMI calculated as previously described. The triceps, subscapular, suprailiac and thigh measurements were obtained with the two callipers. The %BF was estimated using the equations of Peterson *et al.*¹⁵

The correlation coefficient, *r*, was used to evaluate the association between the values of %BF estimated by the two systems, and the values estimated by DXA (%BF DXA). The analysis was made considering the total sample and by gender.

RESULTS

The descriptive statistic of the elderly sample is shown in Table 1. The elderly men were 13.7 kg heavier and 0.15 m higher than the elderly women. However, these mean differences (*p*<0.001) were not reflected in the mean val-

ues of BMI for these two groups (women 26.3 kg/m², men 26.6 kg/m²), where the variances were considered homogenous. The difference between those values was not significant.

A strong positive association between the values of the %BF, with skinfold measurements made with both callipers, was achieved (*r* = 0.997; *p*<0.001). The slope of the regression line is near the unit (0.993), strengthening the agreement between the %BF for both systems.

Considering error estimations, it is possible to conclude that both the standard error (*s_x*) and the Total Error TE presenting values less than 0.5%, meaning that the LipoTool, and so the Adipmeter, can be accepted to be as accurate as the original Harpenden (Table 2).

As observed in Figure 3, the differences (%BF Harpenden-%BF LipoTool) tend to increase with the increase of mean %BF values. This type of variability appears with the intrinsic difficulty of measuring larger skinfolds and limitation of the equipment. In fact, with increase of fat thickness the skinfold is under lower pressure due to the non-parallelism between the jaw surfaces of the skinfold calliper.¹⁶

This analysis proved that the new system performance is similar to the original Harpenden. This means that changes on the original mechanical structure of Harpenden did not interfere with the main Harpenden characteristics, adding new capabilities associated with the intrinsic digital condition.

The descriptive statistic of sample two is displayed in Table 1. The adult men were 20.1 kg heavier and 0.19 m higher than the adult women. However, these mean differences (*p*<0.001) were not reflected in the mean values of BMI for these two groups (women: 23.4 kg/m², men: 25.1 kg/m²), where the variances were considered homogenous. Notice that the age range of the male sample was from 22 to 33 years old whereas the range for the

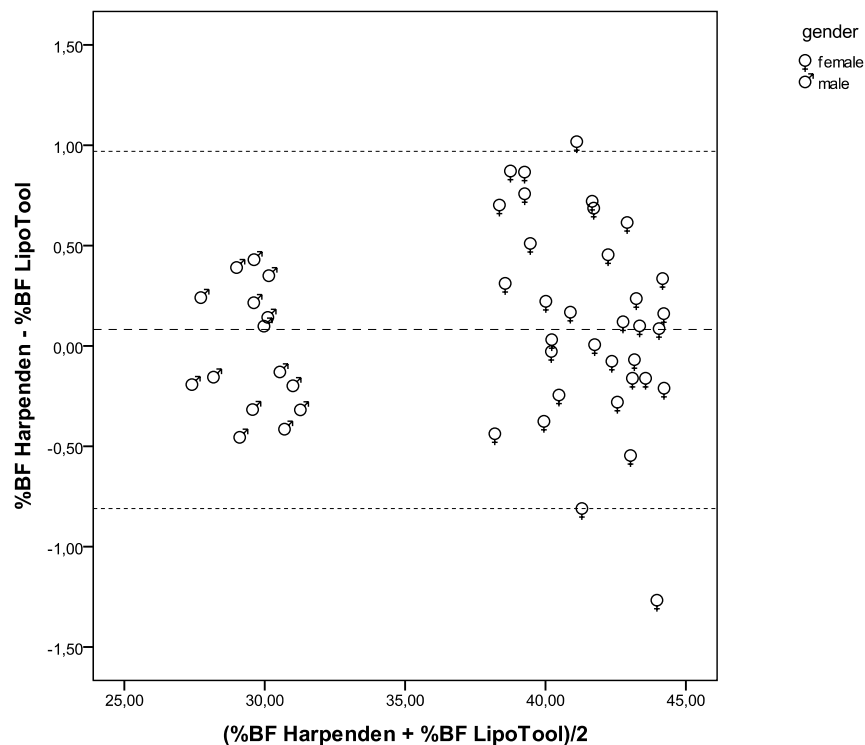


Figure 3. Measurement error Bland-Altman plot for the Harpenden and Adipsmeter_v0 %BF values. (---) mean and 95% limits of agreement (elderly sample).

Table 3. Association between the %BF estimated by *LipoTool* and *Harpenden* against the DXA (adults sample).

	Mean±sd	<i>r</i>	<i>r</i> ²	Intercept	Slope	<i>s_x</i> [†]	TE [‡]
Total (<i>n</i> =40)							
DXA	27.4±8.59	--	--	--	--	--	--
Harpenden	29.5±8.29	0.946*	0.896	4.48	0.914	2.71	3.46
LipoTool	29.2±8.46	0.952*	0.906	3.49	0.937	2.63	3.16
Females (<i>n</i> =25)							
DXA	32.0±5.6	--	--	--	--	--	--
Harpenden	34.0±6.0	0.879*	0.772	4.27	0.931	2.91	3.49
LipoTool	33.8±6.0	0.887*	0.787	3.45	0.950	2.84	3.30
Males (<i>n</i> =15)							
DXA	19.8±7.2	--	--	--	--	--	--
Harpenden	21.9±5.7	0.935*	0.875	7.20	0.746	2.09	3.41
LipoTool	21.4±5.8	0.948*	0.898	6.20	0.770	1.92	2.91

[†]*s_x*, Standard error estimation; [‡]TE, Total error; * *p* < 0.01.

female sample was higher, from 22 up to 58 years (this can be confirmed by the obtained higher value for the standard deviation, 11.5 years).

The average %BF estimated by DXA is within the normal range for both men and women.¹⁷ The different values obtained for the %BF DXA dispersion, was not significant.

There was a strong correlation between the average %BF estimated by DXA and the average %BF estimated either with Harpenden (%BF Harpenden), *r*=0.946 (*p*<0.001) or with LipoTool (%BF LipoTool), *r*=0.952 (*p*<0.001) (Table 3). However, the female and male correlations were significantly different when analysed separately, *r*=0.887 and 0.948, respectively, with LipoTool (*p*<0.001), showing a lower correlation in women than in

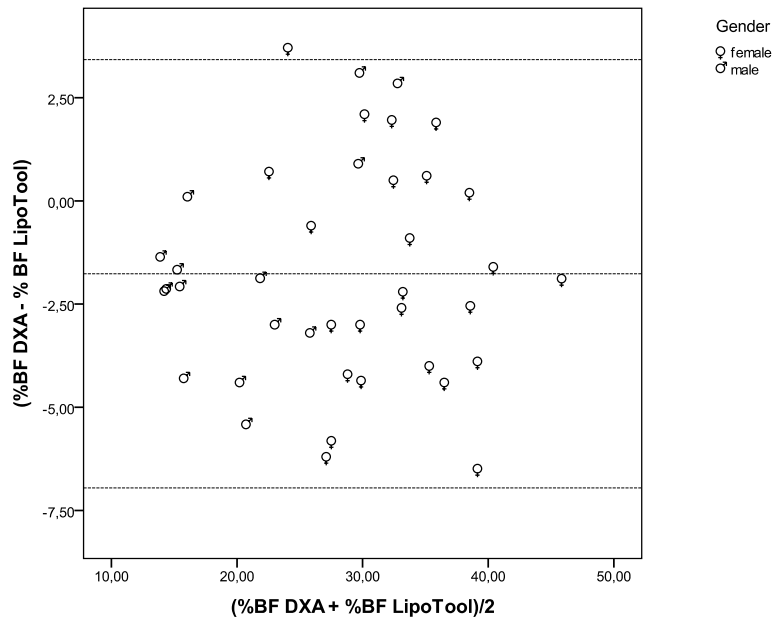
men. Similar behaviour was obtained with Harpenden (Table 3).

The regression line slope is near one for Harpenden and LipoTool, 0.914 and 0.937 respectively, strengthening the agreement between them with comparison to the reference DXA.

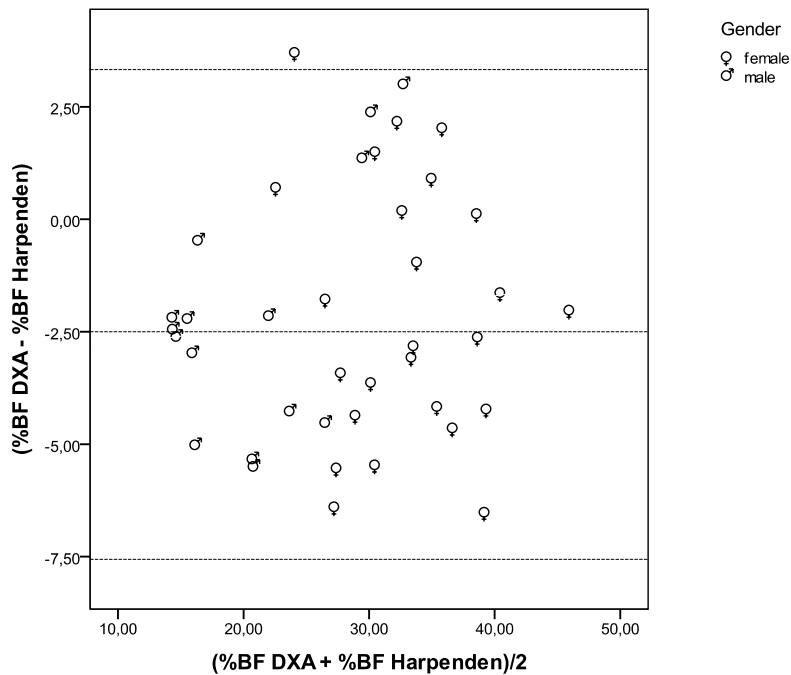
The values of TE obtained slightly higher than 3 could be accepted (between 3 and 4% fat).¹⁸

Bland-Altman shows %BF values by gender for DXA/LipoTool [Figure 4 (a)] and, for DXA/Harpenden [Figure 4 (b)].

The limits of agreements for all samples and by gender are summarized in Table 4. The differences (%BF DXA-%BF Harpenden) according to Bland & Altman¹⁴ plots show that %BF Harpenden overestimate %BF DXA (dif-



4a.



4b.

Figure 4. Bland-Altman plot for the %BF values (a) Adipsmeter_v1/DXA; (b) Harpenden/DXA. (---) mean and 95% limits of agreement (adult sample).

ference mean value -2.12) and presents higher agreement limits (only 1 in 40 adults was outside the agreement limits). Similar behaviours occur for the %BF DXA-%BF LipoTool, however, with a mean value closer to the zero value (-1.77).

Analysing the differences between DXA estimated values and those estimated by both systems, it can be observed that the LipoTool introduces an improvement, in average, of 0.35%. LipoTool measures slightly lower %BF when compared with the original Harpenden, and so slightly closer to DXA, as presented in the results of Table 3 (means' difference are not statistically significant, $p > 0.05$). A deeper discussion of results can be found in Amaral *et al.*¹⁹

DISCUSSION

Although in the present study all measurements were taken by a trained technician, the innovations introduced are supplying considerable aids mainly for technicians with a lower degree of practice, not requiring reading agility, objectivity in time counting and additional skills in combining these tasks with a simultaneous interaction with the individual.

The simplicity, quickness, reliability and accuracy of the skinfold measurement process, as well as the total data recording in a database and, finally, the instantaneous %BF evaluation are the strong features of the system. Its capability for guiding technicians of low proficiency through the procedure also makes it a valuable training system.

Table 4. Mean differences $\pm 95\%$ limits of agreement between SCs and DXA %BF estimations, and between the two systems used ($mean \pm sd^\dagger$) – adults sample.

	Females (n=25)	Males (n=15)	Total (n=40)
%BF DXA-%BF Harpenden	-2.07 \pm 2.87	-2.19 \pm 2.71	-2.12 \pm 2.77
%BF DXA-%BF LipoTool	-1.84 \pm 2.79	-1.64 \pm 2.48	-1.77 \pm 2.65
%BF Harpenden-%BF LipoTool	0.23 \pm 0.37	0.55 \pm 0.49	0.35 \pm 0.45

$^\dagger s_x$, Standard error estimation.

Moreover, it is possible to monitor step by step the measurements quality, accepting or rejecting them if convenient. The requirements concerning the technician training degree are certainly less demanding.

At research level, the system makes available its database for later studies. It also permits easy introduction of new algorithms for %BF evaluation or other functionalities.

The main negative aspects of the first solution, unbalanced handling caused by the interface cable for communication and the calliper weight, was overcome by the introduction of a wireless communication system and the decrease of original calliper weight.

The second solution offers better performance, increasing the simplicity of use and handling, presenting a better weight balance and even weight reduction.

Its battery autonomy is of 9h with a very flexible and easily rechargeable system. Considering the digital sensorization and the data wireless communication system added to the traditional calliper, the cost/benefit ratio is attractive. In fact, three working days of a traditional data recording technician will be enough to support the cost of added electronics to adapt the commercialized Harpenden to the new system.

The use of SC for %BF assessment is based on simple and well established procedures, although with well-known errors and limitations, particularly some of the subjective type. The increase in accuracy offered by the LipoTool strengthened the use of SC as a valid and more reliable method. In fact, it removes from the evaluation performed with the original SC, the inherent subjectivity now overcome by digital measurement, automated procedure and wireless data transmission combined capabilities.

The integration of a database is also valuable. The final printable report is another important issue for summarizing test results. It is the authors' belief that such system, of low cost, will contribute to simplifying the procedure of %BF evaluation, not only by promoting their larger use in clinical practice and in other applications, but also by supplying database resources and further research in the area. This system for measuring skinfold thickness has been patented - PT 103721.²⁰

From the above discussion the LipoTool performance remains equivalent to that of the Harpenden calliper, exhibiting an improvement of 0.35% when referenced to the DXA. This result has no clinical significance. However, it points out the interest of further development to improve this difference and consequently to gain clinical relevance.

Conclusions

The LipoTool, as the traditional SC, is a simple, portable, non-invasive and low cost diagnostic system, based on a

skinfold method, for evaluating the %BF. Although its performance is very similar to that of the traditional Harpenden calliper, according to the present study its results became closer to those obtained by DXA system. Additionally, the wireless communication between the digitally sensorized calliper and a precious step by step guided software application, significantly reduces the %BF evaluation subjectivity and increases the task efficiency and quality control avoiding the involvement of highly trained technicians; and is an important tool for training purposes. In fact, many of its features were devised from its use for training purposes. In general the system represents an upgrade of the skinfold measurement procedure for better reliability, sensitivity and accuracy. Integration of a database guarantees the access to the individual historic data. Therefore, the software implementation of the measurement protocol is easily adjusted to any updates from future studies, which represents to the authors one of the most relevant aspect for other future research. Finally, this system could be easily adjusted to be an assessment tool for teaching purposes.

However it faces serious constraints coming from the use of the original Harpenden mechanical structure: the measuring range is not adjustable for obese individuals; the pressure between jaws is not constant as it is supposed to be (in theory); the jaws surfaces are not parallel to the skinfold in all the opening range; the structure has inherent weight and strongly determines the final cost.

Although not statistically significant, analysis showed LipoTool exhibits better agreement when compared with both original Harpenden and DXA. In any case, the SEE is less than 3% which resulted in the new system being accepted as accurate,¹⁸ and always slightly lower for the LipoTool than for the Harpenden. So, the developed system facilitates the measurement procedure, data collection in a database system, availability for later use makes the system important for training purposes, without increasing random error.

In order to overcome most of those problems a new prototype has been under development with a completely new structure of novel characteristics and better digital sensing and data wireless communication in order to get a lower price and also reliable hardware. At the present it needs to be validated.

Other additional benefits could possibly come from future studies for producing algorithms which could introduce simplicity to the numerous equations needed for the calculations according to the individual age, gender and race.

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AUTHOR DISCLOSURES

All authors declared there is no conflict of interest.

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Original Article

A digital Calliper for training and study purposes

Maria T Restivo PhD¹, Teresa F Amaral PhD^{1,2}, Maria F Chouzal PhD¹, Celina P Leão PhD³, Rita S Guerra MSc^{1,2}, Elisa Marques PhD⁴, Joaquim Mendes PhD¹, Manuel Quintas PhD¹, Jorge Mota PhD⁴

¹UISPA-IDMEC Campus FEUP, Faculty of Engineering, University of Porto, Rua Dr Roberto Frias, 4200-465 Porto, Portugal

²Faculty of Nutrition and Food Sciences, University of Porto, Rua Dr Roberto Frias, 4200-465 Porto, Portugal

³School of Engineering, University of Minho, Campus de Azurém, Portugal

⁴Research Centre in Physical Activity, Health and Leisure, Faculty of Sport Sciences, University of Porto, Rua Dr Plácido Costa 91, 4200-450 Porto, Portugal

訓練及研究目的的電子皮褶卡钳

使用皮褶卡钳是一种快速而有效的评价脂肪百分比的方法。然而，皮褶卡钳有用途和特性方面的局限性，针对此，本研究將传统卡钳(Harpenden)加以改进，並結合软件应用，提出一种新系统。应用這種 LipoTool 测量系统，来获得更佳的精度和可靠性，以及低成本的数据处理和记录方式。首先，為评价 LipoTool 的性能，以 49 位老年人的测量数据与传统的 Harpenden 卡钳进行比较，结果体脂肪百分比的相關性良好。然后，透过加進卡钳和软件之间的无线傳輸，使该系统更提高其功能。并且，该软件可在任何的计算机上操作，可以容入新的模式、线性回归或新的計算式。使用 40 个成人的數據樣本，新系统以标准的双能 X 线吸收儀(DXA)来验证，結果証明效度良好。该方法比传统的皮褶卡钳更可靠和確實，它可以简化脂肪百分比的评估过程，在日常使用中更加有效，減少时间和资源的花费。該系統內建的操作指示讓它成為極優的培训工具，是一种非侵入性、可攜式、不需要特殊准备的测量方法。将来的目標集中在设计更好的机械结构，及增加其它的新颖的功能以供其他研究。

關鍵字：體脂肪百分比、電子式皮褶卡钳、訓練系統、無線傳輸、自動化過程