An automated system for hydrostatic body fat determination including correction for incomplete exhalation

by

Matthew Clark Distel

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Major: Biomedical Engineering
Major Professor: Patrick E. Patterson

Iowa State University
Ames, Iowa
1996

Graduate College
Iowa State University

This is to certify that the Master's thesis of

Matthew Clark Distel

has met the thesis requirements of Iowa State University

Signatures have been redacted for privacy

This thesis is dedicated to all the teachers, coaches, and administrators of the Tiffin City Schools, Tiffin, Ohio. Whether or not you knew it, you have stood behind me every day. Special thanks goes to those listed below from whom I had the honor of learning. Public education can and does work.

Faith Crabtree
Marilyn Barlow
Mrs. Reeder
Jeannie Fodor
Mrs. Miller
Mrs. Morgan
Susan Slemmer
David LeCrone
Milt Place
Nancy Getz
John Lawrence
John Keesey
Lewis Hawk
Louise Ducsay
Mrs. Paulus
Beverly Talbert
Mary Ellen Jacobs
Jane Pease
Larry Kisabeth
Russ Hudgins
Joyce Geyh
Ron Burkett
Mary Miller
Doug Ducsay
Paul Riley
Barbara Hawk
Mike Fansler
Char Pope
Ralph Kizer
Jane Tomaszewski
Tom Nahm
John Munn
Nan Hite
John Spriestersprach
Mike Brickner
Pat Buskirk
Jane Famulare
Betty Cunningham
Matt Miller
Mike Hampp
Curtis King
Lewis Miller
George Thornton
Shelley Hampp
Dave Hershey
Betty Kizer
Ken Carmon
Linda White
Bob Overholt
Ray Weininger
Larry Clausing
Deb Baker
Jean Egbert
Tom Greer
Brian Jakupca
Norm Grimes
Ron Martin
Burton Goetz
Stewart Elder
Joe Silardi
Doug McDonald
Bill Mullett

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

Special thanks goes to the following people without whom this thesis would have been impossible.

To all my family, especially my parents, Scott and Renee, and my sisters, Stephanie and Kimberly, thanks for your unending encouragement and support. Special thanks also to my grand father, Art, and my grandmother, Geri, for your love and confidence in me.

To my grandmother, Harriet, and my grandfather, Ray ("Bub"), an engineer, thank you for watching over me. I wish you could see this, but somehow, I know you can.

To my friends, Ken Han, Derek Chan, Steve Crain, Marvin Williams, and Kichang Lee, thanks for keeping a smile on my face and the situation in perspective. Of all my friends, only you truly know what it is like to go through all this.

To Michelle Hein, thanks for always being there, ready to help in whatever way, and thank you for your patience.

To the ISU Judo, Trap and Skeet, and Men's Glee clubs, as well as the Izaak Walton League of Ames, thank you for the stress relief and the opportunity to remain a human being.

To Dave Thomas, thanks for the motivation.

To the Law Offices of Henderson and Sturm, thank you for the opportunity not only to earn an income, but to gain valuable knowledge and skill while being a part of a team of great people. You all had faith in me when I needed it.

To the ISU Biomedical Communications department, thank you for your aid in making my presentation.

INTRODUCTION

General

Hydrostatic weighing is a widely used and accepted technique in the field of exercise physiology. Its popularity stems from its high accuracy, complete non-invasiveness, and fairly low cost. The technique does, however, have some weaknesses which can lead to error. As this technique is often used to determine body fat for work-related physical standards tests or in athletic training, the highest degree of accuracy possible is always being pursued.

Briefly, the technique involves weighing a subject on land and in water, making an assumption about the amount of air remaining in the lungs after complete exhalation (residual volume), and using this data in a series of widely accepted equations to establish body density and often percent body fat.

Hydrostatic weighing normally employs a spring-based mechanical scale in the water weight determination which has readings that are inherently oscillatory. A trained operator is relied upon to make an estimation of wet weight by visually monitoring the readings of a bobbing gauge needle. This portion of the procedure inevitably raises questions regarding accuracy and subjectivity.

Furthermore, as the technique involves a subject expelling as much air from the lungs as possible and then holding this state while submerged in water for a period often as long as ten seconds, some degree of discomfort is often experienced. A natural tendency is for a subject to unintentionally keep a small amount of reserve air in the lungs (incomplete exhalation). This is undesirable because as little as 100 milliliters of air can change body fat determination by two percentage points for some test subjects.

Hydrostatic weighing also involves a high degree of data collection and organization as well as many calculations by hand using any of a variety of intermediate equations. This is labor intensive, prone to error, and unnecessary considering the capabilities of today's computers.

Previous Work

The idea of replacing a mechanical scale with a force transducer in a hydrostatic weighing system has been in existence for nearly thirty years (1). Fahey and Schroeder (2) have shown that this leads to greater precision in wet weight determination. Much of the preliminary work in this determination involved charting the output and then analyzing the results by hand. This was the case until about ten years ago when McClenaghan and Rocchio (3) designed a system in which the output of multiple force transducers was sampled and underwent analog to digital (A/D) conversion. The period of time for a weighing to take place with this system was about three seconds, the signal was sampled 25 times, and an automated average was made. None of these systems took residual volume (RV) into account or made corrections for incomplete exhalation.

Some of the most progressive research to date has been carried out by Organ et al., (4). Organ and colleagues developed a system that incorporated the best of the previous research in an automated system that included A/D sampling and averaging of load cell signals, plotting wet weight in real time, and made use of an oxygen dilution technique for the determination of a test subject's residual volume while the subject was still in the tank. The necessary instrumentation was incorporated into a computerized system running software written specifically for the testing. However, the details of the averaging process were not made clear. Furthermore, the residual volume analysis required that the subject first exhale completely, hold that position for a few seconds until the weighing procedure was complete, turn a stop cock on the breathing apparatus, and then continue to breathe through the apparatus for another 30-60 seconds. The system also required an interval of four to five minutes (which Organ claimed could have been reduced somewhat) between trials for nitrogen levels in the lungs to return to normal. Thus five to seven trials could take anywhere from 21 to 41 minutes.

Description of System

At its onset, it was the objective of this project to reduce the sources of error in hydrostatic weighing and to increase subject comfort during the procedure. A more accurate determination of wet weight was sought by replacing the mechanical scale with a force transducer accompanied by a computerized data collection and analysis procedure. The time of execution for the weighing procedure was set at about three seconds in order to reduce the time necessary for a subject to be submerged.

A spirometer was incorporated into the system in order to take vital capacity (VC) measurements. VC measurements were made first on dry land and then in the water as the subject was submerged. A dry VC greater than the wet VC was added to the expected RV and thus a correction for any incomplete exhalation was made. The tube also provided an element of security to a subject with regard to the need to inhale while submerged.

The program for operating the load cell and spirometer as well as gathering, saving, storing, and printing test subject information was written in Visual C++ 4.0 by Microsoft. The program is Windows driven and meant to operate in a 32 bit operating system. Computerizing all aspects of data collection and organization (e.g., name, age, race, dry weight) and providing the operator with optional equation selection for the automatic calculation of body fat percentage and residual volume (RV) was accomplished.

While Organ et al. (4) developed an exceptional system, the equipment involved is not available to all users of the technique. Furthermore, that system requires a considerable amount of time for testing to take place. This research incorporates a much simpler determination of effective RV using equipment that is available in nearly all exercise physiology labs (a spirometer) and can carry out five tests on a subject in about fifteen minutes or less. This improvement in testing speed is especially important in cases where large groups of people are being tested for body fat percentage (e.g., an athletic team).

THEORY

Approach to Derivations

The derivations that follow in this section are conceptually well established in the field. However, much of the literature simply presents the results or makes the derivations with little reference to diagrams and models. In the following discussion, force diagrams are used to model the physical systems being analyzed and the derivations proceed directly from this starting point. Every effort has been made to derive these equations in a clear, concise manner with appropriate reference to the actual physical systems being represented by the models. The derivations do, however, follow the general example of Behnke and Wilmore (5).

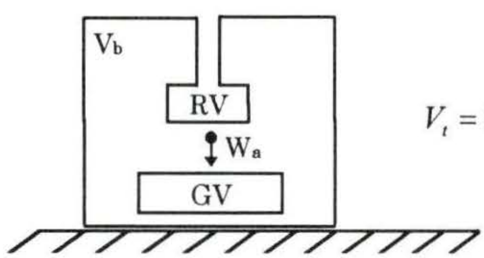
The Ideal Hydrodensiometric Model

Overview

The computation of body fat using hydrodensiometry is a two step process. The first step is to determine the density of the body as a whole with corrections for residual volume (RV) and gastrointestinal flatus (GV). The nature of these corrections, as will become clear in the following derivation, is to eliminate RV and GV from consideration as part of the body. Thus, the density calculated is the average density of the body alone. It should be pointed out that body volume is not segmented into compartments at this stage of the calculation. The second step in determining body fat is to assume the body is made of two components, fat and non-fat, and then to use the determination of overall body density to find the proportion of fat to non-fat. This second step will be detailed later.

Derivation of Hydrostatic Determination of Body Density

Figure 1 represents the body on dry land. Body volume is represented by V_b. The downward force experienced due to the acceleration of gravity is termed air weight (sometimes "dry weight"), W_a. The total volume of the body, V_t, is comprised of V_b, RV, and GV.



$$V_t = V_b + RV + GV$$

Figure 1. Model of Body on Dry Land

After W_a has been determined using a conventional scale, the body is dipped in water until completely submerged. With this done, by Archimede's principle, the body experiences an upward force equal to the weight of the water displaced. This buoyant force, F_b, is calculated by multiplying the total volume of the body, V_t, by the weight of water per unit volume, D_w. D_w is temperature dependent. Fortunately, the density of water over the temperature range of interest is well known.

It should be pointed out the D_W is properly termed *specific* density as its units are weight per volume. Despite the fact that a density is, by definition, in units of *mass per volume*, much of the literature in this field uses density to mean *weight per volume*. Thus, in order to follow this convention, it will be understood in the discussion that follows that density is in units of weight per volume.

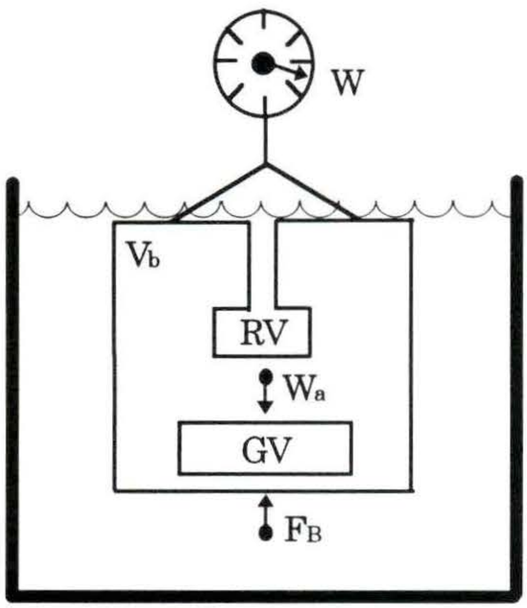
With these considerations in mind, the submerged body is modeled as shown in Figure 2. The weight of the body while submerged (as perceived by a scale from which a subject is suspended) is termed water weight, W_W, and is equal to the dry weight, W_a, minus the buoyant force, F_B. Writing this last statement as an equation, the total volume of the body, V_t, can then be calculated.

$$W_W = W_a - F_B$$

$$W_W = W_a - V_t D_W$$

$$V_t D_W = W_a - W_W$$

$$V_t = \frac{W_a - W_W}{D_W} \tag{1}$$



Archimede's principle gives:

$$F_B = V_t D_W$$

Figure 2. Model of Body in Water

By recognizing that the volume of the body is equal to total volume minus RV and GV, and making the above substitution for V_t, we can write:

$$V_b = V_t - (RV + GV)$$

$$V_b = \left(\frac{W_a - W_W}{D_W}\right) - (RV + GV) \tag{2}$$

Then, directly from the definition of density, and using the above substitution for V_b, we arrive at the expression for body density, D.

$$D = \frac{W_a}{V_b} = \frac{W_a}{\left(\frac{W_a - W_W}{D_W}\right) - (RV + GV)} \tag{3}$$

Derivation of Hydrostatic Determination of Body Fat

Once the density of the body is known, the calculation of body fat moves to its second step. By modeling the body as a two component mass, each component having its own weight and volume, we can find the proportion of fat weight to total weight, which is the goal, i.e., body fat percentage (Figure 3).

The intuitive validity of this model is sound. If a body were made entirely of one of the components, i.e., it were pure, it would have a certain weight and density. If the body were made entirely from the other component,

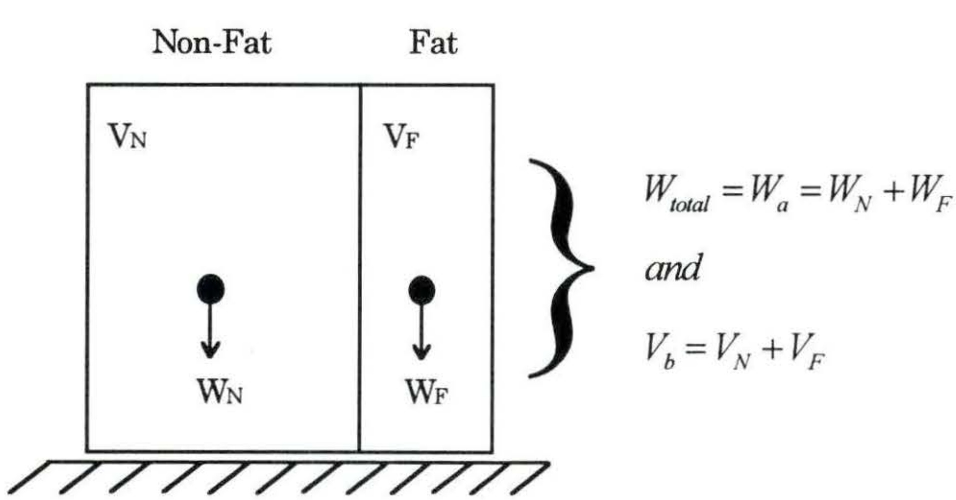


Figure 3. Body Modeled as Two Components: Fat and Non-fat

it would have a different weight and density. It follows that if the body were made of a hybrid of the two components, some value intermediate to the pure values would be found for weight and density. If the density of the two component materials and the overall density of the body are known, the proportion of one component's weight to the overall weight can be determined.

With this model in mind, the derivation of percent body fat is fairly straightforward. The starting point is the definition of overall body density, D, which was found in the previous derivation.

$$D = \frac{W_a}{V_b} = \frac{W_a}{(V_N + V_F)} \tag{4}$$

We then solve for volume using the general definition of density.

$$D = \frac{W}{V} \Rightarrow V = \frac{W}{D} \tag{5}$$

Using this, substitutions are made for the fat and non-fat volumes, V_N and V_F, in the denominator of equation 4.

$$D = \frac{W_a}{\left(\frac{W_N}{D_N} + \frac{W_F}{D_F}\right)} \tag{6}$$

In order to eliminate the weight of non-fat, W_N, from this equation, it is recognized that the weight of non-fat is equal to dry weight minus the weight of fat.

$$W_N = W_a - W_F$$

Substituting this into equation 6, the following equation results.

$$D = \frac{W_a}{\left(\frac{W_a - W_F}{D_N} + \frac{W_F}{D_F}\right)}$$

With this done, a solution for W_F/W_a is found. This value is the body fat percentage.

$$D = \frac{W_a}{\left(\frac{W_a - W_F}{D_N} + \frac{W_F}{D_F}\right)}$$

$$D = \frac{W_a}{\left(\frac{W_a}{D_N} - \frac{W_F}{D_N} + \frac{W_F}{D_F}\right)}$$

$$D=\frac{W_a}{\left(\frac{W_a}{D_N}+W_F\left[\frac{1}{D_F}-\frac{1}{D_N}\right]\right)}\cdot\frac{\left(\frac{1}{W_a}\right)}{\left(\frac{1}{W_a}\right)}$$

$$D=\frac{1}{\frac{1}{D_N}+\frac{W_F}{W_a}\left(\frac{1}{D_F}-\frac{1}{D_N}\right)}$$

$$\frac{1}{D}=\frac{1}{D_N}+\frac{W_F}{W_a}\left(\frac{1}{D_F}-\frac{1}{D_N}\right)$$

$$\frac{W_F}{W_a}=\frac{\left(\frac{1}{D}-\frac{1}{D_N}\right)}{\left(\frac{1}{D_F}-\frac{1}{D_N}\right)}=\frac{\left(\frac{1}{D}\right)}{\left(\frac{1}{D_F}-\frac{1}{D_N}\right)}-\frac{\left(\frac{1}{D_N}\right)}{\left(\frac{1}{D_F}-\frac{1}{D_N}\right)}$$

$$\frac{W_F}{W_a}=\frac{1}{D\left(\frac{1}{D_F}-\frac{1}{D_N}\right)}-\frac{1}{D_N\left(\frac{1}{D_F}-\frac{1}{D_N}\right)} \tag{7}$$

With the substitutions made for D_N and D_F, equation 7 is the form most often seen in the literature. The most widely known equations are those of Siri and Brozek et al. Siri proposed the density of fat and non-fat to be 0.900 and 1.100 respectively; whereas Brozek proposed values of 0.889 and 1.103 (all quantities in g/mL; values calculated by the author from the equations below and equation 7). With these values substituted into equation 7, the following well known equations result (13, 18, 19).

$$Siri{:}\ \%Fat=\left(\frac{4.950}{D_b}-4.500\right)100$$

$$Brozek\text{: } \%Fat = \left(\frac{4.570}{D_b} - 4.142 \right) 100$$

Development of Real World Model

Overview

No ideal model holds in the real world and the ideal hydrodensiometric model is no exception. Limited by instrumentation, human judgment, and environmental factors, the actual physical system deviates from the ideal model. Corrections must be made in order to counteract these sources of error. The development and use of a realistic model provides a way to do this.

Correction for Incomplete Exhalation

As some test subjects find keeping their lungs in an expired state while submerged to be uncomfortable or unnatural, it is not unreasonable to assume that air which is not part of the RV space sometimes remains in the lungs during submersion. This, of course, provides an added buoyant effect which eventually translates to an increased determination of body fat percentage.

In an effort to account for this unexpired air, the system at hand incorporates the use of a vital capacity measurement. Vital capacity (VC) is the maximum amount of air that can be voluntarily exhaled after a complete inhalation. A subject's VC is measured first on land in order to eliminate the possibility of a submersion-induced reluctance to completely exhale. Then, while wet weight is being determined, VC is measured again. The positive

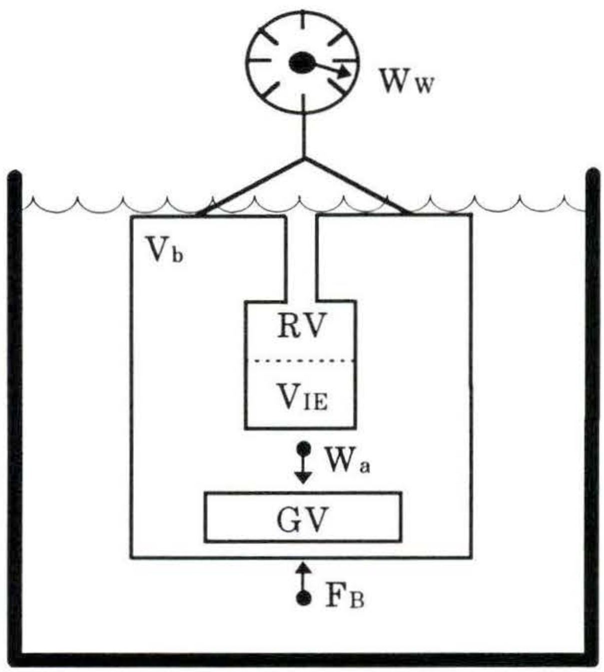


Figure 4. Model of Body in Water with Air Incompletely Exhaled

difference between VC_{dry} and VC_{wet} (VC_{dry} - VC_{wet}) is the volume of air incompletely exhaled, V_{IE}. To correct for V_{IE}, it is helpful to refer to Figure 4 (below) and equation 2 as previously derived.

Examining equation 2, it is seen that RV and GV are eliminated from consideration as part of body volume by simply subtracting them from total volume (as defined by equation 1). Following this approach, V_{IE}, is added to RV and GV and this sum is subtracted from total volume. In this way, a correction for the additional buoyant effect of V_{IE} is made and a more accurate value for body density (and consequently body fat percentage) results. Thus, the following equation is used for body density when the incomplete exhalation option is used.

$$D = \frac{W_a}{V_b} = \frac{W_a}{\left(\frac{W_a - W_W}{D_W}\right) - (RV + GV + V_{IE})}$$

The Residual Volume Problem

Determining a test subjects' RV, as defined earlier, while submerged is not a trivial matter. The use of a gas dilution technique usually provides the most accurate information with regard to this quantity, but this necessitates the use of special gas analysis equipment. The use of an anthropometric equation based on height, age, and sex (16) is often used to estimate the RV with the assumption that a test subject expires all possible air from the lungs.

The system being described here allows for the use of either approach. If estimation is used, RV is determined automatically from the parameters entered for a particular test subject. While the system does not include any gas analysis equipment, an option exists to enter a known RV previously determined by any technique an operator desires. If, for example, the operator uses a highly accurate oxygen dilution apparatus to determine RV, the result of that determination can be entered into and used by the system.

Determination of Wet Weight

While the determination of dry weight is usually a simple matter of using a conventional scale, the determination of a submerged subject is more complicated. Several factors contribute to this problem. The fact that a test subject must be held in a state drastically different from normal activity naturally lends to unwanted movement, especially with subjects who are unfamiliar with the technique. An imperfect, but nevertheless useful, analogy to this factor is that it would be difficult to weigh a live fish on a dry scale. Another common occurrence is for a test subject to exhale to the point he or she believes is complete and then, either through encouragement or determination, to forcibly exhale a few more small amounts of air. The abdominal push required for these extra exhalations, in addition to the change caused by the loss of the excess air, invariably causes the wet weight value to fluctuate noticeably. Also, the fact that a test subject moves at all while in the weighing tank introduces waves and currents in the water. These forces cause the subject to move in all directions, causing fluctuations in wet weight. While this problem can be attenuated by having a subject use slow, gradual movements, it is unlikely that it will ever be completely eliminated. Lastly, as the mechanical scales used for finding wet weight are often spring-based, they are inherently oscillatory. All these factors lead to a wet weight that is typically perceived over time as illustrated in Figure 5.

The problems with comfort and repeated exhalation mentioned above can be partially eliminated through the use of the technique for determining incomplete exhalation as previously described. If the amount of air incompletely exhaled can be determined, a subject would need to exhale only as far as is comfortable. The need to blow out those extra few milliliters of air is eliminated. Furthermore, as the tube used for measuring the volume of air exhaled allows air to flow in both directions, an added element of security is provided to the subject. While inhaling through the tube would invalidate a test, at least the subject could breathe if the need were felt.

The spring based oscillation can be reduced simply by using a load cell in place of the mechanical scale. The oscillation caused by waves and currents, however, is more difficult to compensate. Referring again to Figure 5, it is typically seen that a point is reached where the test subject has exhaled as much air as is comfortable and is being as still as possible. This is

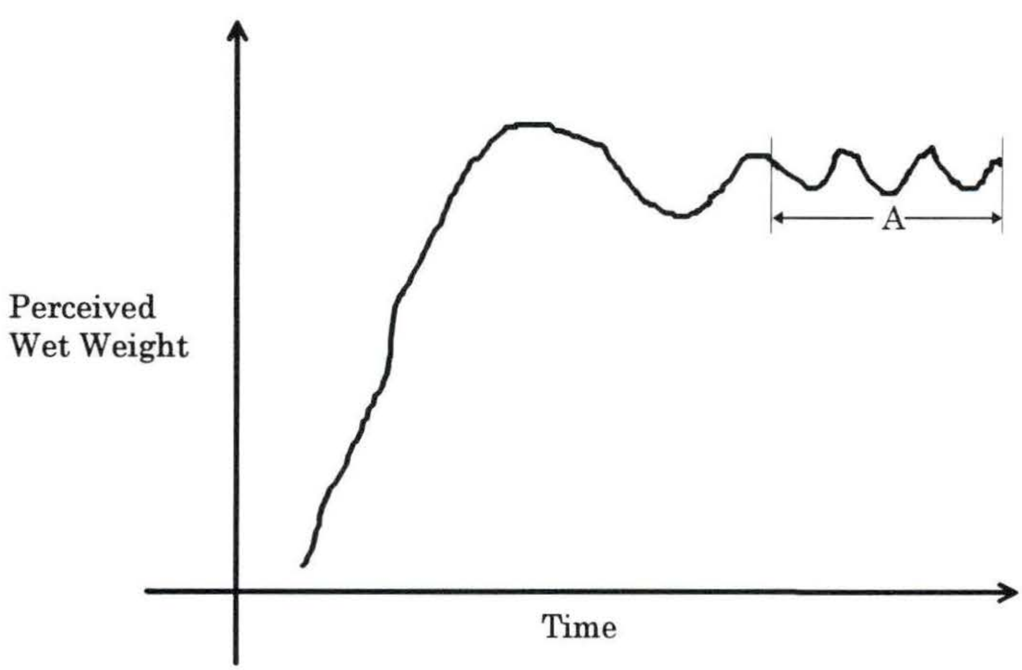


Figure 5. Typically Perceived Wet Weight Over Time

represented by the region marked by "A". Region A is typically where an operator estimates a subject's wet weight when a spring based scale is used. At this point, the scale indicator would be oscillating about some range of weight which the operator would visually inspect. An estimation of a single value for wet weight, based on this oscillating range, would then be made. Not only does this raise questions with regard to objectivity, but subject discomfort becomes a limiting factor. Remember that, at this point, the subject is submerged with all possible air exhaled (ideally) and is trying to remain as still as possible. Holding this state for as little as ten seconds is difficult even for experienced test subjects. Consequently, the operator must be quick in estimating wet weight, and the statistical advantage of taking readings over a longer period of time is lost.

The system at hand examines region A within a time period of approximately three seconds, sampling wet weight at approximately 3300 Hz. Referring to Figure 6, the basic approach to this technique will be described here while the software for this process will be detailed later in the Materials and Methods chapter under *Detailed Description of Computer Software, Weighing Procedure.*

In Figure 6, the dots and crosses represent samples of the load cell signal. By finding the peaks and valleys of this sampled signal, as marked by the crosses, and averaging them, a good estimation of true wet weight is obtained. That is the essence of the weighing procedure. In a way, this mimics what a human operator would do with a mechanical scale. The advantage, however, is that a computer keeps track of all the readings and takes an objective average. (The way in which *HydroStats* accomplishes this is described below in Materials and Methods under *Averaging Sampling Results*.)

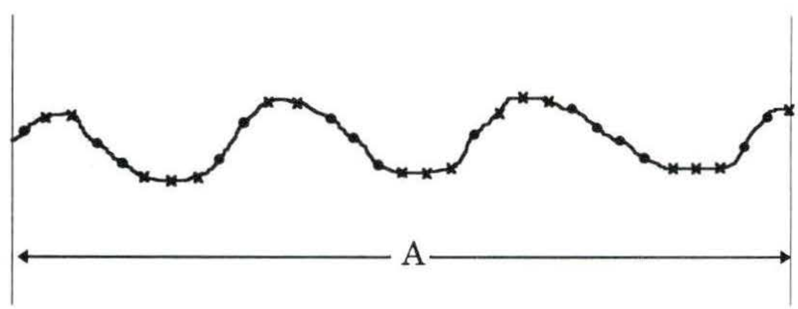


Figure 6. Region and Points Involved in Finding Wet Weight

MATERIALS AND METHODS

System Overview

A highly automated system was developed consisting of four main physical parts (Figure 7).

- A computer system (monitor, CPU, keyboard, printer, and mouse).
- A load cell by Magnetek Transducer Products, Nashville, Tennessee, model AWUA, 50 pound range.
- A spirometer by KL Engineering Co., Sylamr, California, model Pneumoscan S-301C, AC with D/A converter.
- Logic circuit and signal conditioning housing, constructed by the author specifically for this system, containing load cell power supply and signal conditioner, and other electronics required by the system, hand soldered by the author. Load cell power supply and signal conditioner is manufactured by Kube Electronics, Inc., Moorpark, California, model KE 4051.

Load Cell

The load cell is a force transducer. Thus, when power is applied to it, its output voltage varies in a well-defined way in relation to the amount of strain

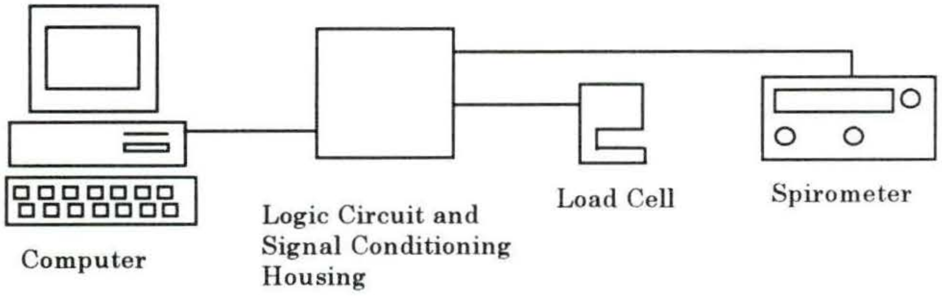


Figure 7. Physical Components of Weighing System

that is applied. In this way, the wet weight of a test subject (a force) can be gauged after proper amplification and processing.

Spirometer

The function of the spirometer is to independently measure the volume of air that is expelled from a test subject's lungs. The spirometer has a digital output indicating this volume which, after appropriate handling, is used by the computer in the calculation of an incomplete exhalation.

Logic Circuit and Signal Conditioning Housing

Housed within this "black box" are the electronics necessary for interface between the computer, load cell, and spirometer. This housing contains the analog signal amplifier and summing amplifier necessary for conditioning the load cell signal into a form that is usable by the computer. The housing also contains the multiplexers used to channel the twelve output bits of the spirometer to the three input bits of the A/D board in the computer. The details of these interfaces are given later in this chapter.

Computer

The computer contains an analog to digital (A/D) conversion board which is necessary for interfacing with the analog-based load cell. The A/D board is also capable of four digital outputs and three digital inputs that are used to control and scan the multiplexed interface with the spirometer.

In addition to these hardware control and interface functions, the computer is responsible for running the software *HydroStats*. This application was written specifically for this system using Visual C++ 4.0 by Microsoft for use in a Windows 95 environment. *HydroStats* is the central controller and processor of information gathered by both user input and instrumentation.

Summary of General Interaction of Physical Components

A summary of the interactions between the physical components is in order. Briefly, the system software, *HydroStats*, is responsible for taking input from the system operator regarding a test subject's vital statistics (e.g., name, height, dry weight, and age) through a Windows based interface. With this done, a test subject's wet weight is determined using the load cell while the volume of air remaining in the lungs of the test subject is determined using the spirometer. Both of these functions are also under *HydroStats*' control. The interface between the computer and load cell or spirometer is carried out through the components in the logic circuit and signal conditioning housing. Once all the parameters necessary for the determination of body fat have been gathered, *HydroStats* carries out the necessary calculations (using equations chosen from several options by the user) and displays the results. The operation of individual components will now be explained in detail.

A/D Board

General

The DAS-8 A/D board by the Keithley Metra Byte Corporation, Taunton, Massachusetts, is capable of accepting eight analog inputs (single-ended), three digital inputs, and providing four digital outputs (6). While eight analog inputs are possible, only one channel, selected through a software controlled multiplexer, may undergo an A/D conversion at a time. A/D conversions can be performed on inputs ranging from -5 to +5 volts DC. The DAS-8 is highly versatile and capable of additional timing and counting functions; however, the basic attributes just mentioned are of primary importance to this project.

Hardware Interface

The DAS-8 is a peripheral card-type package that can be installed in any available slot on the motherboard of a computer operating with an 8086-based microprocessor. It has a dip switch selector which allows it to occupy eight consecutive addresses in I/O space anywhere from hex 100 to hex 3FF; however, as some of that space is usually reserved or otherwise occupied, the use of hex 300, 308, or 310 as a base address is recommended by Keithley. This project used hex 300 as its base address. The driver software for the DAS-8 needs to be installed on the hard disk of the computer using the DAS-8 and is defined in the CONFIG.SYS file by the following line of code.

DEVICE = DAS8DI.SYS/B: &h300

Software

The DAS-8 was also accompanied by a miniature software library of about twenty-five "modes" which are BASIC functions that allow simplified software control of the A/D board. However, as the software for the system at hand was written using Visual C^{++}, these BASIC functions were not used. All control of the A/D board by *HydroStats* is carried out via original C^{++} code.

Address Map

As previously mentioned, the DAS-8 occupies eight consecutive addresses in I/O space (Table 1). This information is an abbreviated version of the table found in the DAS -8 manual (6) (p. 3-2).

Status and Control Registers

As can be seen in Table 1, the status and control registers occupy the same I/O address. The status register provides the operating software (in this case, *HydroStats*) with information regarding the operating state of the A/D board through a read from BASEADDRESS+2. In contrast, a write to the control register, also at BASEADDRESS+2, allows the controlling software to change the operating state of the DAS-8.

Table 2 shows the significance of each bit in the status register. This table is adapted from the DAS-8 manual (6) (p. 3-4).

Table 1. Abbreviated Address Map of Keithley DAS-8

Address	Read	Write
BASEADDRESS + 0	A/D Low byte	Start 8-bit A/D conversion
+2	A/D High byte	Start 12-bit A/D conversion
+3	Status register	Control register

Table 2. Bitwise Explanation of Status Register

Bit	Significance	
7	EOC End of conversion	
6	IP3 Digital input 3	
5	IP2 Digital input 2	
4	IP1 Digital input 1	
3	IRQ Interrupt request	
2	MA2 (MSB)	Analog input multiplexer indicator, bit 2
1	MA1	Analog input multiplexer indicator, bit 1
0	MA0 (LSB)	Analog input multiplexer indicator, bit 0

Bit 3 was not of interest for this project. Bit 7, end of conversion, is an indicator of whether an A/D conversion on one of the analog inputs has been completed once it has been initiated. Bits 4-6 are digital inputs that allow external devices to interface with operating software through the A/D board. They are independent of one another. Bits 0-2 are actually considered collectively in their interpretation as a 3-bit number that indicates the analog input channel currently selected for A/D conversion by the internal multiplexer. Simply put, the binary number formed by bits 0-2 (bit 2 being the most significant) is the number of the analog input being converted to digital form. For example, if bit 2 is 0, bit 1 is 1, and bit 0 is 1, the binary number formed is 011, or decimal 3. Thus analog input 3 is selected for A/D conversion.

A write to BASEADDRESS+2 allows access to the control register. Table 3 is an adaptation of the information appearing in the DAS-3 manual (6) (p.3-5).

Table 3. Bitwise Explanation of Control Register

Bit	Significance
7	OP4 Digital output 4
6	OP3 Digital output 3
5	OP2 Digital output 2
4	OP1 Digital output 1
3	INTE Interrupt enable
2	MA2 Analog input multiplexer set, bit 2
1	MA1 Analog input multiplexer set, bit 1
0	MA0 Analog input multiplexer set, bit 0

Bits 4-7 are digital outputs that are independent of each other. Writing to these bits resulted in their being directly reflected at the output pins of the A/D board. This configuration allows the controlling software to operate external devices through the DAS-8. Bit 3 is not used in this project whereas bits 0-2 are the direct counterparts of bits 0-2 of the status register. That is, writing to bits 0-2 of the control register (using the same binary scheme as the status register) allows controlling software to select the analog input from among the eight possibilities for A/D conversion.

Initiating and Reading the Results of an Analog to Digital Conversion

Referring to Table 1, it can be seen that a write to BASEADDRESS+0 OR BASEADDRESS+1 will initiate an A/D conversion for 8 bits or 12 bits, respectively. *HydroStats* uses only the 12 bit conversion option and thus begins all its A/D conversions with a write to BASEADDRESS+1. The results of the A/D conversion, once it is complete, are then available through a read from BASEADDRESS+1 (high byte) and BASEADDRESS+0 (low byte). The use of a high and low byte is necessary because a single byte is only eight bits long. As *HydroStats* makes use of the 12-bit A/D conversion, two bytes (with four bits in excess) are required to give a complete result. Table 4a and Table 4b show the format of the A/D Results posted to BASEADDRESS+0/+1.

The high and low bytes are combined into a single number in software through the use of the C^{++} shift operator (>>) and bitwise OR operator (|). By shifting the high bit four places to the left, then shifting the low byte four places to the right, and then OR-ing the results, the true result of the A/D conversion is obtained. The following example illustrates this process.

Assume the high-byte obtained from BASEADDRESS+1 is 10111011 and the low byte obtained from BASEADDRESS+0 is 10010000. Note that the four least significant bits of the latter will always be 0's, as indicated in Table 4b. Shifting the high byte four places to the left results in 101110110000 whereas shifting the low byte four places to the right results in 00001001. It is assumed that this second result has leading zeroes, therefore it could be written in a 12-bit format as 000000001001. By performing a bitwise OR of these results, we arrive at our final result: 101110111001 (decimal 3001).

Table 4. High Byte (a) and Low Byte (b) of A/D Conversion Results

a		b	
BASEADDRESS+1, Bit	Significance	BASEADDRESS+0, Bit	Significance
7	B1	7	B9
6	B2	6	B10
5	B3	5	B11
4	B4	4	B12
3	B5	3	0
2	B6	2	0
1	B7	1	0
0	B8	0	0

Note that the high and low bytes are intact in the final 12-bit binary result in the left eight and right four bits, respectively.

The only remaining issue with regard to carrying out an A/D conversion is that of the controlling software collecting the data as just described at the appropriate time. This is due to the fact that an A/D conversion does require a significant amount of time to perform once it has been initiated by a write to BASEADDRESS+1, as described above. As gathering the results before the conversion is complete will result in incorrect information being obtained, it is vital that the conversion be complete before the results are gathered. This is accomplished by polling the end of conversion (EOC) bit of the status register before reading the results. As *HydroStats* does not make use of the DAS-8's interrupt capabilities, the EOC bit is polled repeatedly until it is low, which is an indication that an initiated A/D conversion has been completed. As previously stated, the EOC bit is located in Bit 7 of the status register. Thus, by reading the status register and then masking bits 0-6, the controlling software can determine whether an A/D conversion is complete. This masking is accomplished by performing a logical AND between the control register's bits and the binary number 10000000 (decimal 128). If the result of this AND is 128, the conversion is ongoing; if it is 0, the conversion is complete. The entire process just described occurs in this order: begin the conversion, wait until the conversion is complete, gather the results.

Interpretation of A/D Conversion Results

The DAS-8 is capable of converting single-ended analog inputs in the range of -5 to +4.9976 volts DC (VDC) with the digital result being in a 12-bit binary format. Thus twelve 0's corresponds to -5 VDC while twelve 1's corresponds to 4.9976 VDC. The resolution is 0.0024 VDC for 1 binary unit.

Table 5. Digital Code for Result of A/D Conversion

Binary	Decimal	Analog Input Voltage (VDC)
0000 0000 0000	0	-5.0000
0000 0000 0001	1	-4.9976
.		
0100 0000 0000	1024	-2.5000
.		
1000 0000 0000	2048	±0.0000
.		
1100 0000 0000	3072	+2.5000
.		
1111 1111 1111	4095	+4.9976

Table 5 is an adaptation of information found in the DAS-8 manual (6) (p. 3-3) and illustrates the interpretation of an A/D conversion.

Digital I/O

Digital input and output through the DAS-8 is straightforward. As previously mentioned, bits 4-7 of the control register are digital outputs while bits 4-6 of the status register are digital inputs. Simply reading from the input bits or writing to the output bits allows the controlling software to poll or control devices external to the computer. While these inputs and outputs are independent, they may be used collectively. This concept is utilized by

HydroStats and will be covered in this chapter in the section entitled *Software for Reading the Spirometer*.

Load Cell

General

The load cell used by this system is the Magnetek AWUA which has a 0-50 pound (tension) load limit. The load cell and its associated electronics are illustrated in Figure 8. A supply voltage of +10.0 VDC is recommended by the manufacturer and was used in this system. The load cell has both its power supply and amplifier contained in a single unit, Kube Electronics' KE 4051. The KE 4051 is supplied by standard 115 volts AC, 60 Hz power and provides both a 10.0 VDC power supply and an amplifier capable of enlarging the load cell's small DC signals to levels up to 10 VDC (rated) and slightly over 11 VDC (measured). The gain of the amplifier within the KE 4051 was approximately 282.

Range Considerations

While the amplified signal output of the load cell is capable of being anywhere from 0-10 VDC, the Keithley A/D board previously described is only capable of converting analog inputs in the range of -5 to +5 VDC. In a simple test, the load cell had a measured output of 22.2 mV for a 0-pound load and 28.3 mV for an 11-pound load, corresponding to amplified outputs of 6.47 and 8.19 VDC, respectively.

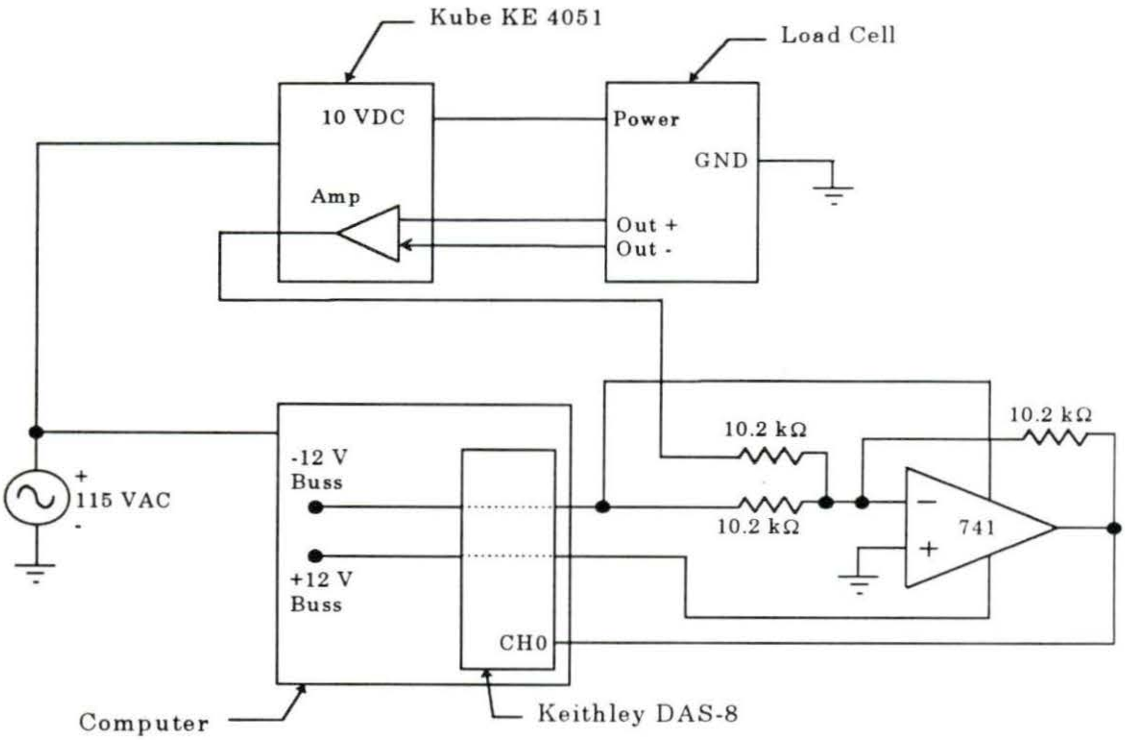


Figure 8. Schematic of Load Cell and Associated Electronics

Extrapolating this data gives an estimated amplified output of 14.25 VDC with a 50-pound load. Thus, for the range of the load cell (0-50 pounds), amplified outputs of 6.47 to 14.29 VDC could be expected. Figure 9 illustrates this situation, where the dotted line represents extrapolation.

There are two problems with this situation. First, in order for an A/D conversion to be carried out by the A/D board, the range of the amplified load cell signal must fall between -5 and +5 VDC. Second, the amplifier can only reliably amplify signals to levels between 10 and 11 VDC. Thus, loads of

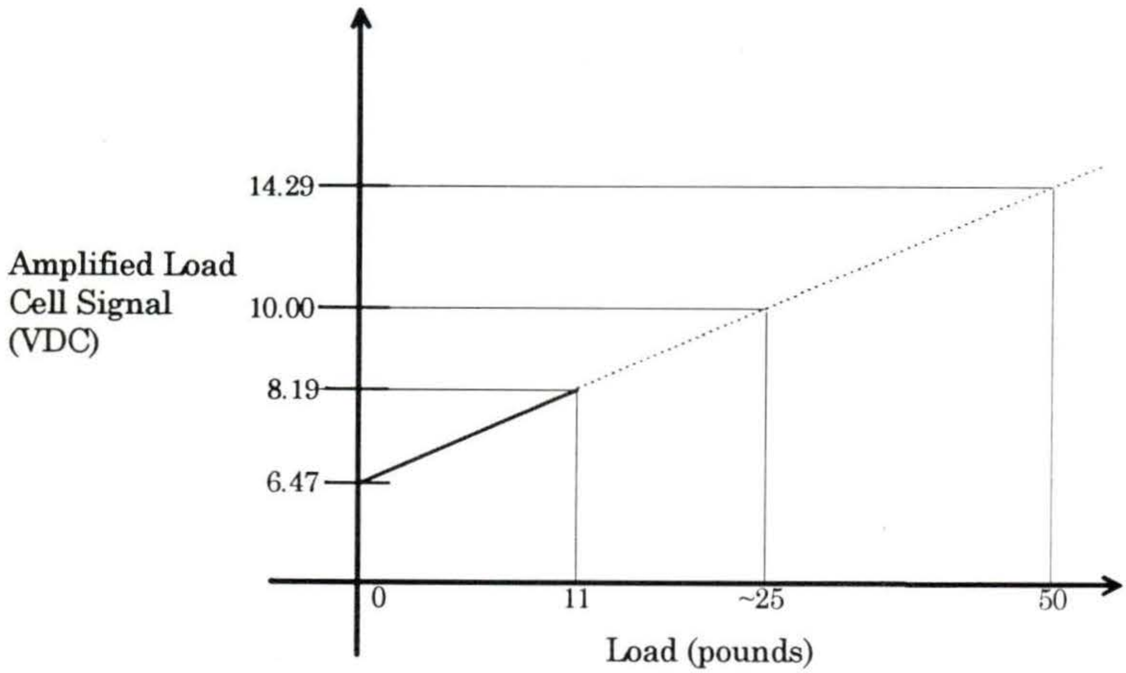


Figure 9. Amplified but Unadjusted Load Cell Signal

greater than about 25 pounds will all yield amplified outputs of approximately 11 VDC.

The first problem can be remedied by shifting the level of the output downward using a summing amplifier (described below). The second problem can be ignored by recognizing that loads encountered in the wet weighing stage of hydrostatic body fat determination should only rarely approach 10 kg (or approximately 22 pounds). Thus the range of loads reasonably to be expected should result in amplified load cell outputs being well within the linear range of the amplifier.

Summing Amplifier

As just described, shifting of the amplified load cell signal is necessary for compatibility with the A/D board. This is accomplished through the use of a summing amplifier (7) with two inputs. At one input, the amplified load cell signal is applied, while at the other input, a constant -12 VDC voltage is applied. A second voltage of -12 VDC was chosen because the A/D board has access to the PC's -12 VDC buss at one of its output pins, thereby providing a readily available, steady voltage supply. The design of the amplifier follows and makes reference to Figure 10. A standard 741 op-amp supplied with ±12 VDC (positive 12 VDC also from the PC buss) was used for this purpose.

By recognizing that an op-amp constrains V_I to be equal to V_N, which is grounded (and therefore at 0 VDC), the following mathematical statement can be made.

$$V_I = V_N = 0$$

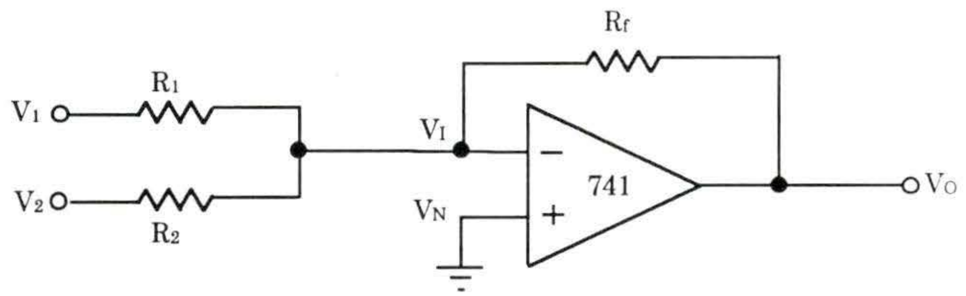


Figure 10. Summing Amplifier Used to Shift Amplified Load Cell Signals

An expression for the output voltage, V_O, can be obtained by writing a node voltage equation involving the two input voltages, V_1 and V_2, the input resistors, R_1 and R_2, and the feedback resistor, R_f.

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_O}{R_f} = 0$$

$$V_O = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right)$$

By setting all the resistors to the same value, i.e., $R_f = R_1 = R_2 = R_S$, we see that V_O is the inverted sum of V_1 and V_2.

$$V_O = -R_S\left(\frac{V_1}{R_S} + \frac{V_2}{R_S}\right)$$

$$V_O = -R_S(V_1 + V_2)$$

$$V_O = -(V_1 + V_2)$$

If one input, V_1, is the amplified load cell signal, V_{LC}, and the other input, V_2, is a constant -12 VDC, the output of the summing amplifier becomes the inverted form of V_{LC} minus 12 VDC.

$$V_O = -\left(V_{LC} + (-12)\right)$$
$$V_O = -\left(V_{LC} - 12\right)$$

Therefore, assuming a load of 0-25 pounds results in an amplified load cell output of 6.47 to 10.38 VDC, this range shifted negatively by twelve volts results in a range of -5.53 to -1.62 VDC. The summing amplifier inverts these values, providing the final, conditioned, expected load cell output range, 5.53 to 1.62 VDC. This is illustrated in Figure 11.

While 5.53 VDC for a load of zero pounds is still slightly beyond the range of acceptable input for the A/D board, it should be pointed out that between the dipping chair, the chains from which the chair is suspended, and the minimum wet weight of a subject to be reasonably expected, the total weight will always cause the output voltage of the summing amplifier to fall below the 5 volt mark. A load of at least 3.4 pounds is adequate for driving the summing amplifier's output into this range. Thus, so long as the chair, chains, and submerged subject weigh at least 3.4 pounds, the A/D board will yield an accurate wet weight.

Spirometer

General

A spirometer, the Pneumoscan S-301C, by K. L. Engineering , was used in this system. It is a digital meter utilizing a turbine type flow transducer

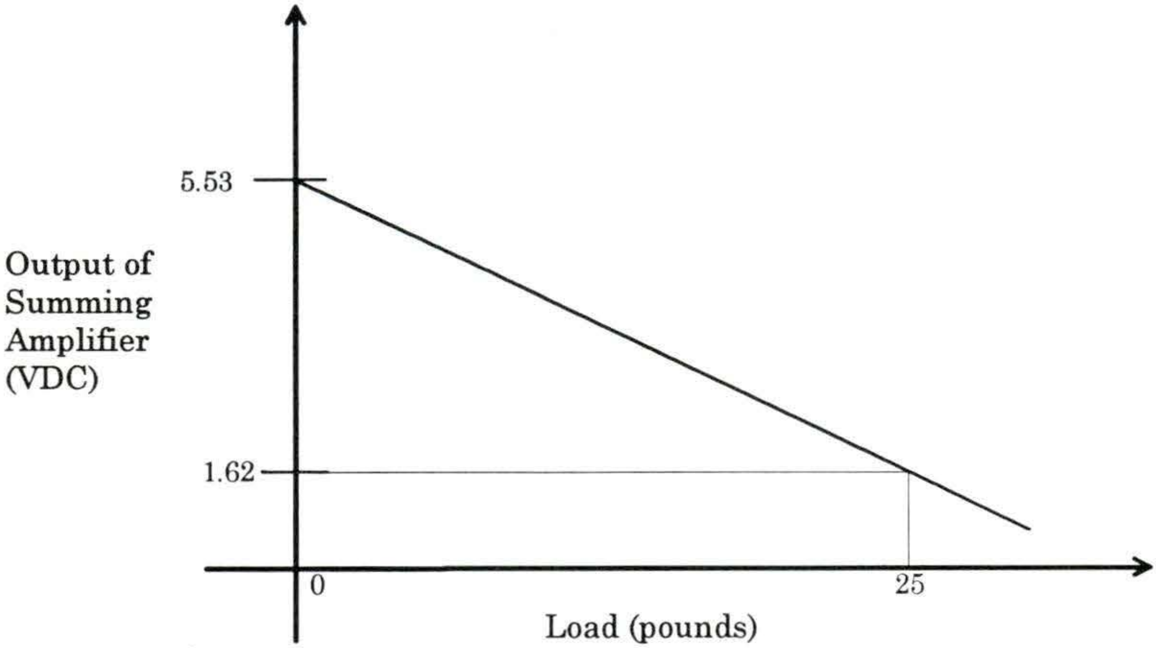


Figure 11. Expected Output of Inverted, Shifted Load Cell Signal for Expected Load Range

and is capable of numerous types of pulmonary measurements; however, this system utilizes only the vital capacity (VC) measurement. While the display of the S-301C shows VC measurements only to 0.1 liters, its output is available to 0.01 L. This output is directly available in a 12-bit, complementary binary coded decimal (CBCD) format via a centronics-type parallel connector at the rear of the spirometer.

I/O Considerations

While the VC of a test subject as measured by the spirometer is readily available in a 12-bit digital format, interfacing this output with the rest of the system required special consideration, especially with regard to the Keithley

DAS-8 A/D board. As described earlier, the DAS-8 only has three digital inputs. Therefore, multiplexing of the twelve outputs to the three inputs became necessary. Furthermore, it was discovered that one of the inputs of the particular DAS-8 used by this system was defective and therefore unusable. This situation was remedied by using a spare analog channel and then performing an A/D conversion to determine whether a logic high or logic low was present. The details of this configuration will be made clear below.

74LS153 Multiplexer

The solution to the multiplexing problem mentioned above involves the use of two standard 74LS153 (153) integrated circuits (IC's). The 153 is a dual, four-input multiplexer having two selection bits that control both of the multiplexers. The logic symbol and truth table for the 153 are shown in Figure 12 and Table 6. These are adaptations of the information found in a common TTL data book (8).

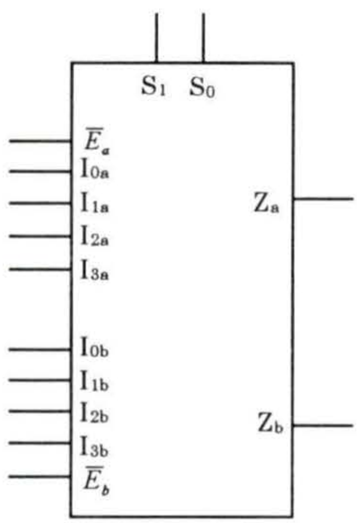


Figure 12. Logic Symbol for 74LS153 Multiplexer

Table 6. Truth Table for 74LS153 Multiplexer

Select Inputs		Enable (a or b)	Inputs (a or b)				Output (a or b)
S_1	S_0	$\overline{E}$	I_0	I_1	I_2	I_3	Z
-	-	H	--	--	--	--	L
L	L	L	L	--	--	--	L
L	L	L	H	--	--	--	H
L	H	L	--	L	--	--	L
L	H	L	--	H	--	--	H
H	L	L	--	--	L	--	L
H	L	L	--	--	H	--	H
H	H	L	--	--	--	L	L
H	H	L	--	--	--	H	H

H High voltage
L Low voltage
-- Don't Care

In words, this means that for an individual multiplexer (one of two on a given 153), the select inputs, S_1 and S_0, determine which of the four inputs, I_0 to I_3, will appear at the output, Z. For example if S_1 and S_0 are 1 and 0 respectively, then binary 2 is selected. If input I_2 is low, then output Z will also be low; if I_2 is high, Z will be high. On a given 153, the same select bits are used for both multiplexers, therefore, using the example just given, I_{2a} appears at Z_a while I_{2b} appears at Z_b.

Multiplexing Scheme

By using two 74LS153's, the multiplexing problem between the spirometer and the DAS-8 was solved. Figure 13 illustrates this solution. The power supply for the IC's, V_{CC}, was provided directly from the DAS-8 while

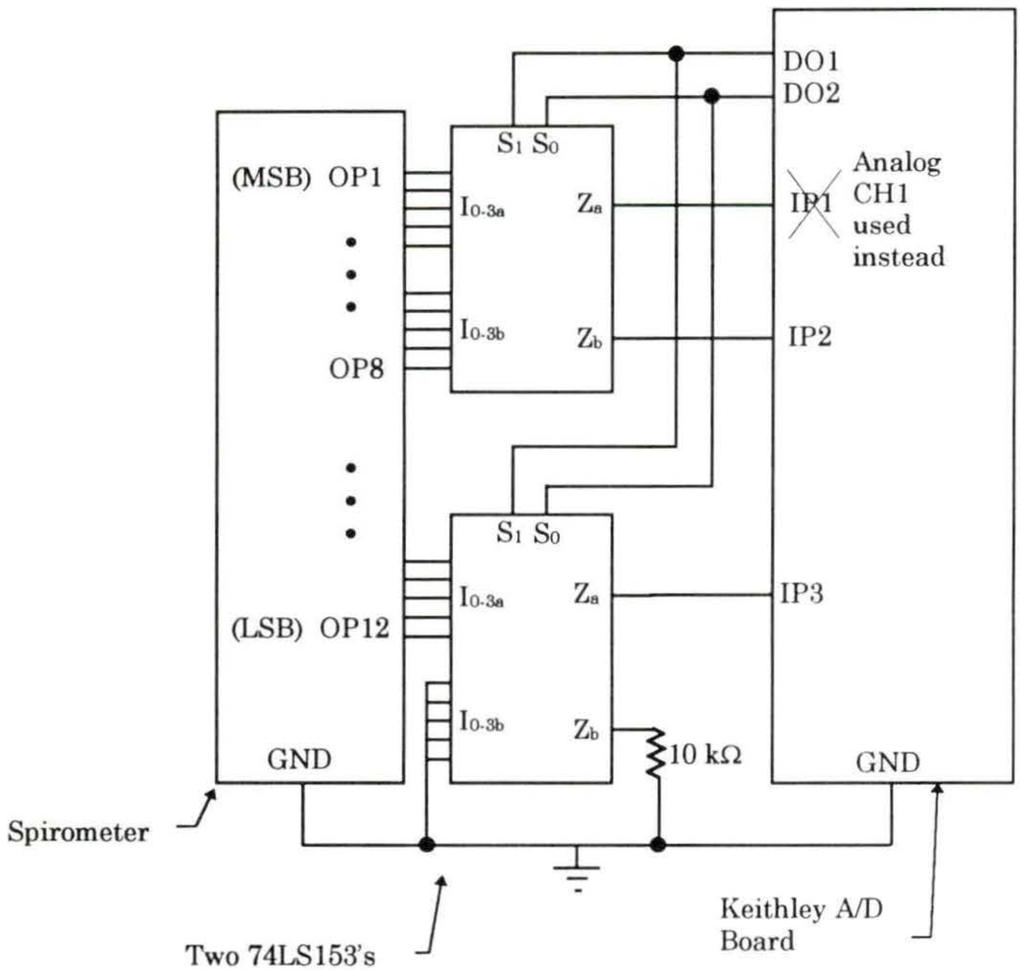


Figure 13. Overall I/O Configuration of Spirometer

control of the 153's through the select bits was accomplished through software via writes to the DAS-8's digital outputs. (The details of this control will be given later in this chapter in the section entitled *Software for Reading the Spirometer* under *Detailed Description of Computer Software.*) The spirometer has each of its 12 output bits fed into an input of a 153. As only twelve bits are needed, the remaining four inputs on the second 153 are grounded. The output of the second '153 is grounded through a 10 kΩ resistor and is ignored.

The outputs of the multiplexers are in turn fed to the digital inputs of the A/D board through manipulation of the select bits. As previously discussed, one of these digital inputs (IP1) was nonfunctional and had to be channeled to a spare analog input (CH1). There, an A/D conversion for the determination of the logic state of the output of the first 74LS153's a-multiplexer takes place. The digital outputs of the A/D board are incremented from binary zero to binary three so that all twelve spirometer output bits are eventually read into *HydroStats* through the three inputs on the A/D board.

Spirometer Output Scheme -- Complemented Binary Coded Decimal

As mentioned above, the output of the spirometer is in a 12-bit complementary binary coded decimal (CBCD) format. With normal binary coded decimal (BCD), each four bits represent a single decimal digit. For example, 0101 1001 0111 would correspond to 5 9 7. CBCD works identically except that each bit is complemented (changed to its opposite). Therefore, 5 9 7 would be 1010 0110 1000 in CBCD. *HydroStats* reads each spirometer output bit in turn, complements it in software, and then interprets the results in BCD terms.

One other point concerning the spirometer's output should be mentioned. Assuming the quantity is in liters, the decimal place of the CBCD number is understood to come after the first digit. That is to say spirometer bits 1-4 represent ones of liters, bits 5-8 represent tenths of liters, and bits 9-

12 represent hundredths of liters. Continuing the example, an output corresponding to decimal 5 9 7 is understood to mean 5.97 liters.

Detailed Description of Computer Software

General

The software for this system was named *HydroStats* and was written in Visual C++ 4.0 by Microsoft. *HydroStats* was a Windows-based program meant to run in a 32-bit operating system such as Windows 95.

User Interface

Main Frame

HydroStats' form matches other Windows 95-based programs closely. A main frame marks and encloses all windows created by the application and has its own menu options. All normal application scope functions (opening, closing, printing, exiting, calibration, etc.) are present.

Client Card

The usual notion of the view of a document takes form in *HydroStats* through the "client card", a window containing all the information necessary to determine the body fat percentage of a single test subject. The client card takes operator input with regard to the following information: name, age, height, dry weight, sex, and race. The operator is also given choices for the body fat and residual volume equations through the use of pull-down menus. The body fat equation choice is between the Siri and Brozek equations while the residual volume choice is between the Goldman-Becklake estimation (based on age, height, and sex) or entering a known residual volume determined by using a technique external to the system. The Goldman-Becklake estimation uses the following equations (16):

$$\textit{Men: } RV = 0.017(\textit{age in years}) + 0.06858(\textit{height in inches}) - 3.477$$

$$\textit{Women: } RV = 0.009(\textit{age in years}) + 0.08128(\textit{height in inches}) - 3.9$$

The client card also displays the results of a single wet weighing including: wet weight, expected RV, average dry VC, wet VC, any incomplete exhalation, resulting effective RV, body density, and body fat. Where appropriate, these quantities are automatically calculated and displayed as soon as the necessary information has been gathered. For example, if the Goldman-Becklake RV estimation is selected for the RV equation, as soon as height, sex, and age for a particular client entered, expected RV is displayed. Furthermore, if any input provided by the user changes, all quantities are recalculated. For example, after a client is weighed and all results are displayed, the operator wishes to see the results using a different body fat equation and residual volume. By simply changing these values, all results are automatically recalculated and displayed. This process, however, applies only to currently displayed results; results recorded in the memory slots (see below) are not affected.

HydroStats contains five memory "slots" for each client card. A single slot is a space for recording all of the results mentioned in the previous paragraph. The client card has buttons for recording the set of results in a slot, viewing the results already recorded, and clearing all the slots. This configuration allows the operator to evaluate the validity of a trial before recording it. The display also automatically indicates which of the five slots is about to be filled as well as when all slots are full. The viewing of recorded results is accomplished through a standard print preview where an average of each of the results (as appropriate) is also displayed.

A client card may be saved at any time with all recorded information being stored. Furthermore, as *HydroStats* uses a multi-document interface, several client cards can be in use within the main frame at one time.

Use of the Spirometer

To use the spirometer for an incomplete exhalation correction, all that is necessary is to click on the corresponding checkbox on the client card. This will cause a spirometer calibration dialog box to appear on the display. The instructions in this dialog appear as follows:

1. Clear the spirometer. Disinfect if necessary.
2. Instruct test subject to inhale completely, then exhale as much as possible in one smooth breath through the spirometer tube.
3. Click on "Trial Complete".

4. Repeat steps 1-3 until three trials have been completed. Allow adequate time between trials to prevent hyperventilation. The process may be restarted at any time.

In this way, three trial values for expected VC are obtained. Individual trial results are displayed as they are collected. Once the operator is satisfied with these results, a click on the accept button causes the dialog box to close and an average of the three dry VC values to appear in the average dry VC indicator in the results area of the client card.

When a test subject is weighed while using the spirometer, a reading of the spirometer is taken at the end of the weighing procedure (described below) and is displayed on the client card under "wet VC" in the results section. The difference between average dry VC and wet VC (assuming the latter is the smaller of the two), is displayed as "incomplete exhalation". Any incomplete exhalation is added to the expected RV in order to obtain "effective RV". (See *Development of Real World Model*).

Test Subject Weighing Procedure

Once all the necessary information for a test subject has been entered (including establishing an average dry VC if the spirometer is used), the weighing procedure may be initiated by clicking the weigh button on the client card. This action causes a pre-weigh dialog box to appear on the display that instructs the user as follows:

1. Test subject should now be on chair in water.
2. If using spirometer, be sure it is reset.

3. Instruct test subject to submerge and exhale (through tube if using spirometer).

4. Once test subject has stopped exhaling, click OK.

5. Weighing procedure will take about 3 seconds. When "Done" message appears, let subject back above water.

When the test subject has finished exhaling, clicking on the OK button causes the load cell weighing procedure to occur. As the instructions indicate, this process takes about three seconds and results in a value for wet weight being obtained using the process described under *Determination of Wet Weight*.

Software for Reading the Spirometer

In light of the procedures described under *Spirometer*, the following algorithm describes the operation of the *HydroStats* function that reads the spirometer.

1. Write to the digital outputs of the A/D board, causing the next (or perhaps first) set of three spirometer output bits to be selected by the multiplexers.

2. Initiate an A/D conversion on the analog channel being used as a substitute digital input.

3. Wait for the conversion to be complete.

4. Obtain the results of the conversion.

5. Interpret the results of the A/D conversion: voltage of greater than 2.5 V is logic 1, else bit is logic 0.

6. Reassemble the bits in BCD to obtain a three digit number.

7. Divide the three digit number by 100 to obtain spirometer output in liters, i.e., match spirometer display.

Software for Reading and Averaging the Load Cell Signal

Obtaining a Single Load Cell Reading

The software for reading the load cell a single time is contained within a *HydroStats* function written specifically for the DAS-8 A/D board. The algorithm that follows describes this function's operation.

1. Initiate A/D conversion on analog input receiving conditioned load cell signal.

2. Wait for A/D board to finish conversion.

3. Read digital results of conversion.

Sampling the Load Cell Signal Over Time

Sampling of the load cell signal over time is accomplished by a function that repeatedly makes a call to the function that takes a single reading. Ten thousand samples are taken and placed in a storage array which is subsequently analyzed in another function described below. The algorithm for the sampling function is as follows:

1. Call function that returns a single, digital load cell reading.

2. Put result in next (or first) element of storage array.

3. Repeat steps 1-2 until 10,000 samples have been obtained.

A timing delay was also introduced into the function just described in order to increase its execution time to about three seconds. This timing delay actually occurs after step two during each iteration.

Averaging of Sampling Results

The software for identifying and averaging the peaks and valleys of the load cell signal (see Figure 5 and Figure 6) functions as follows. Given a perfectly sinusoidal signal, as in Figure 14, it would be possible to easily identify the peaks and valleys. By examining the signal one point at a time, if the point in question were greater than the points one time unit to either side, the point would be a peak; if the point were less than both its neighbors, it would be a valley.

However, actual signals cannot be expected to behave in the ideal way. Using the criteria for peaks and valleys just described on a less smooth, real signal would lead to misidentified peaks and valleys (indicate by X's in Figure 15).

HydroStats addresses this problem by examining the points ten time intervals to either side of the point of interest, i.e., it examines a window that is twenty time intervals wide. In this way, false peaks and valleys caused by irregularities in the signal are ignored (Figure 16). The algorithm for the function that accomplishes this is as follows:

1. Examine next (or first) point and points ten time intervals behind and ahead.
2. If the point is greater than both of the other two, it is a peak; if it is less than both of the other two, it is a valley.
3. If a peak or valley is found, store it in an array.
4. Repeat steps 1-3 until all ten thousand samples have been examined.

5. Find the average of all peaks and valleys.

This procedure identifies several points in a peak or valley area. All points represented by dots in Figure 16 are identified and averaged, and this is the result of a weighing procedure. This model depends on the assumptions that the signal is fairly sinusoidal (as is the case with hydrostatic weighing) and that the true value of wet weight is not changing with time. The latter

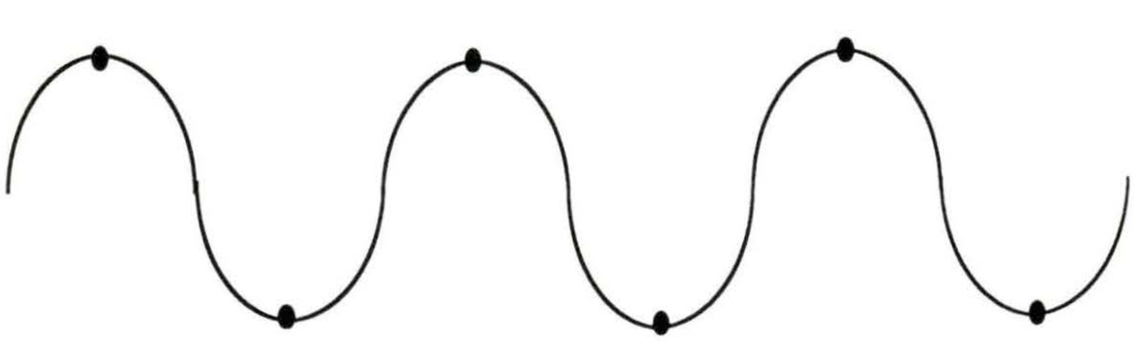


Figure 14. Peaks and Valleys of an Ideal Sinusoidal Signal

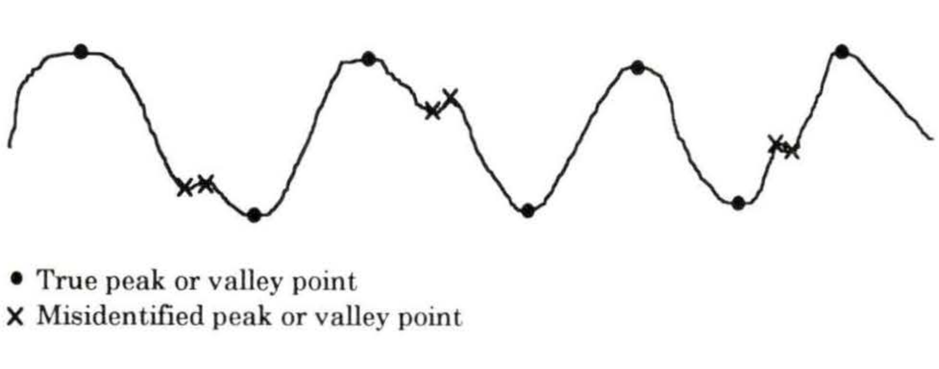
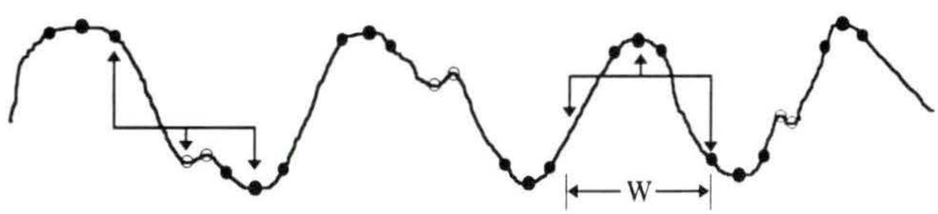


Figure 15. Peaks and Valleys of a Real Signal Using Ideal Criteria

assumption would not be valid, for example, if the test subject inhaled or exhaled during the weighing procedure because this would cause a change in true wet weight.

This function was validated in separate trials. (See below in *Validation Experiments* under *Sampling and Averaging Function* and in Results, under *Sampling and Averaging Function.*)



- True peak or valley point
- ○ Previously misidentified peak or valley
- W Twenty time unit window

Figure 16. Peaks and Valleys Using a Time Window

Calibration

Water Temperature

Calibration of water temperature is accomplished through user input using a dialog box that automatically appears at start up. Water temperature may be modified at any other time through the calibration menu of the main frame. While the user may enter this quantity in either degrees Fahrenheit or degrees Celsius, the temperature is always stored in °C in a file called H2Otemp.hys in the c:\caldat directory. This directory is automatically created the first time *HydroStats* is run on a particular computer.

H2Otemp.hys also contains the densities of water from 15-40 °C in a look up table in half degree increments (see Appendix) based on the data of Weast (11) and Harris (12). Half degrees were interpolated from the whole degree values. When the time comes in the weighing procedure to determine body density, this file is opened, the entered water temperature is retrieved, and the density of water at this temperature is found. This value is used as D_W in the denominator of equation 3.

Load Cell

The user is also prompted for calibration of the load cell at start up time, and this parameter can also be verified or re-established at any time through the calibration menu of the main frame. As with water temperature, the information gathered is stored in a file in the c:\caldat directory. The file for the load cell calibration data, however, is called "LCcal.hys".

The load cell is calibrated with two known weighted conditions which allows the formation of a calibration curve. One of the weighted conditions must be the zero load state for the chair, with any weights used to cause a test subject to be weighed down, e.g., a weight belt, on the chair. This zero load state should be conducted with the chair and weights submerged. The other weighted state is with a known weight added to the zero-load state. The dialog box that controls load cell calibration allows the user to enter any known weight. While any known weight within the system's range of 25 pounds would suffice, it is suggested that a calibration weight greater than the weight of expected wet weights be used. This allows for interpolation of wet weights on the calibration curve rather than extrapolation. Furthermore, the known calibration weight may be loaded directly onto the load cell above water (with the chair and any other weights still submerged) or, if the underwater weight of the known calibration weight is known, it may be put on the chair (also with the chair and any other weights still submerged).

Actual calibration of the load cell begins with a dialog box that displays the actual numbers returned from the A/D board for both the zero load weighted condition and the known calibration weighted condition as well as an edit box that allows the user to directly input the value of the known calibration weight. The A/D values read "(N/A)" at start up since, at that point, no data is available. By clicking on the calibrate button of this dialog box, step by step instructions are given to the user through two subsequent dialog boxes (one for the zero load weighted condition, the other for the known calibration weighted condition) that use the weighing procedure previously described to retrieve the A/D values that result. After checking to make sure that the results are reasonable (known calibration weighted state has a value that is neither equal to nor greater than the zero load weighted state), the results are displayed in the original load cell calibration dialog box. The user may either accept these values by clicking on the OK button or conduct the procedure again.

The three values obtained are then stored in a file in the c:\caldat directory. When the time comes to interpret the averaged results of a load cell weighing, this file is opened and a calibration curve is easily computed (Figure 17).

This curve is defined by the following well known equation, where y represents the average output of the load cell and x represents the load.

$$y = mx + b \tag{8}$$

The slope of the line, m, is rise over run while the y-intercept, b, is simply the A/D board output for zero load. Mathematically:

$$m = \frac{(A\,/\,D\ \textit{value at known weight})\ -\ (A\,/\,D\ \textit{value at zero load})}{\textit{Known calibration weight}}$$

$$b = (A\,/\,D\ \textit{value at zero load})$$

When the *HydroStats* function that computes wet weight opens the file, it obtains the A/D outputs for the two calibration states and the value of the known calibration weight. It uses these values in the two equations above to

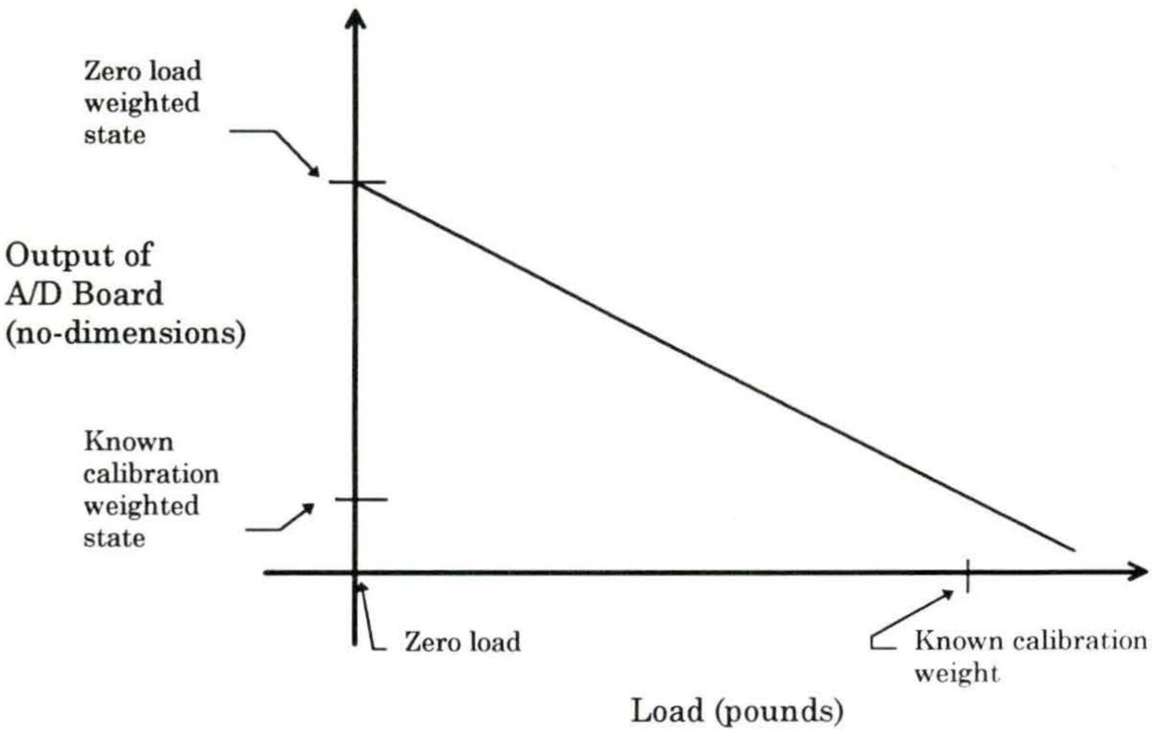


Figure 17. Calibration Curve for Load Cell

define the calibration curve. Solving equation 8 for x (load) in terms of y, m, and b (A/D output, computed slope and y-intercept of the calibration curve, respectively) we arrive at the equation used for determining a weight (x) given an A/D board value (y).

$$x = \frac{(y-b)}{m}$$

Description of Validation Experiments

Static A/D Board Testing

In order to verify that the A/D board gave consistent readings for known loads, the output of the A/D board was tested in a series of fifteen trials. Each trial consisted of loading the load cell first with only the chair and chains and then with a known weight. Thus two outputs for each trial were obtained. Two brass counterweights normally used with a balance scale were used as the known weight. While these two counterweights were nominally rated at five pounds each, they were measured using PC 8000 digital scale (by Mettler Instruments, Brighton, New Jersey) and found to have an actual combined weight of 4524.8 grams, or 9.9755 pounds.

Sampling and Averaging Function

The sampling and averaging function used by *HydroStats*' weighing procedure to find the average of an approximately sinusoidal signal was tested independently before it was actually incorporated into the system. This was accomplished through a simple experiment that involved manually applying an approximately sinusoidal force to the load cell. While a mechanical vibrator (or other source which would have produced a smoother load cell signal) could have been used as a load, it was felt that manually applying the load would provide a more random signal thus more accurately reflecting the conditions encountered with hydrostatic weighing.

Of the ten thousand samples that were collected, the points that were identified as peak or valley points were recorded and plotted. These results were qualitatively inspected to ensure that the function was operating in the desired way.

Static Weight Testing

The weighing procedure used by *HydroStats* to calculate wet weights was further tested by obtaining calculated weights while using a series of known weights. Containers filled with varying amounts of water were used to create eighteen known weights that ranged in size from 0 to 8413.7 grams (0 to 18.55 pounds).

Each known weight was measured using a Mettler PC 8000 digital scale (accurate to 0.1 grams) before it was placed on the chair. (For the sake of simplicity, these trials were conducted with the chair , chains, and known weights out of the water.) After calibrating the load cell, a known weight (as determined by the digital scale) was placed on the chair and *HydroStats* was used to measure its value. Each known weight was measured in this way ten times with the weight being removed and then replaced on the chair between each trial.

Static Simulation of a Human Subject

In order to simulate an actual test subject, a test was developed that determined the wet weight of a known weight and a sealable container partially filled with water (Figure 18). By varying the amount of water in the container (and consequently the amount of air in the container), different lung volumes were simulated. The results of the weighings were compared to expected values.

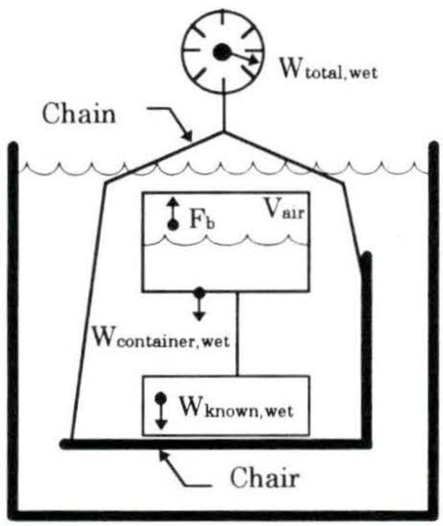


Figure 18. Static Simulation of Human Subject

In order to carry out this test, the wet weight of the container itself, $W_{container,wet}$, and the known weight, $W_{known,wet}$, were determined first. The internal volume of the container, $V_{container}$, was then determined by filling it with water of a known temperature (water from the hydrostatic weighing tank) and weighing it. After subtracting the weight of the container itself, the volume of the water inside the container was determined using equation 5. The container was then emptied and partially refilled. By weighing this amount of water and determining its volume, V_{water}, (again using equation 5 with the container weight tared), the volume of air in the container, V_{air} could be found.

$$V_{air} = V_{container} - V_{water}$$

With V_{air} determined, the expected total wet weight, $W_{total,wet}$ of the chair, chains, partially filled container, and known weight was calculated using equations 9 and 10 where F_b represents the buoyant force of the air, D_W represents the density of water, and g represents the acceleration of gravity.

$$W_{total,wet} = W_{container,wet} + W_{known,wet} - F_b \quad (9)$$

$$W_{total,wet} = W_{container,wet} + W_{known,wet} - V_{air} D_W g \quad (10)$$

Total wet weights for four different volumes of air in the container were tested and the results were compared to the expected values.

Human Subject Testing

General

For validation purposes, fourteen human test subjects had their body fat percentages determined with both the established method (mechanical scale, visual estimation of oscillating indicator, hand calculation, etc.) and the system at hand. Test subjects included six males and eight females ranging in age from twenty-one to thirty-two years. All but two of the subjects had previously had their body fat percentage determined using the established method. A consent form explained an outline of the procedure, encouraged questions, and made clear that their participation could be terminated by them at any time without prejudice of any kind. All were in good health.

Before testing began, the load cell was calibrated using a weight known to have a wet weight of 9.22 pounds, and water temperature was entered as appropriate.

Testing Procedure

After completing the consent form and having an opportunity to have questions about the procedure answered, test subjects were asked to put on a nose clip for the remainder of the experiment. The Siri body fat equation and Goldman-Becklake RV estimation were used for all participants. After the subject's name, age, height, dry weight, race, and sex were entered, the determination of a dry VC was carried out. As described above, this consisted of three trials in which the subject was instructed to first inhale completely and then to exhale as much as possible. These trials were conducted with the subject in a standing position.

The test subject was then asked to get into the weighing tank, wet the hair, and remove all air bubbles from the swimsuit and body hair. With this done, the test subject was seated on the chair, handed the spirometer tube, and given the following instructions:

1. Inhale completely, then exhale completely in one breath through the spirometer tube while submerging yourself. Don't worry about any extra exhalations ("blooping") after the first long breath.
2. When we see that you have finished exhaling, we will begin the weighing process. This will take about three seconds; during this time try to remain as still as possible.
3. When the weighing procedure is complete, we will pound on the side of the tank to let you know that you can come back up.

Five trials were conducted using this procedure. The determination of the test subjects' body fat percentages using the established method was conducted independently within an hour of the tests using *HydroStats*. These results were reported to the author at a later time.

RESULTS

Static A/D Board Testing

The results of the static A/D board testing as previously described are in Table 7. Given the these results, the resolution of the system can be found by dividing the calibration weight by the change in the A/D output. Thus, 9.222/ (4032-3410) is 0.015 pounds per unit of A/D output.

Table 7. Results of Static A/D Board Testing

	Load Cell Reading	
Test Number	0 Load	Known Cal. Weight
1	4033	3410
2	4032	3410
3	4032	3410
4	4032	3409
5	4032	3410
6	4032	3409
7	4032	3410
8	4032	3410
9	4032	3410
10	4033	3411
11	4032	3410
12	4032	3410
13	4032	3410
14	4032	3410
15	4032	3410

Sampling and Averaging Function

The results of the qualitative test of the load cell averaging function are given below in Figure 19 (peak points) and Figure 20 (valley points). The signals shown in these figures are irregular as would be expected of a manually applied sinusoidal load. Of the ten thousand samples taken in this particular trial, 1256 met the peak criteria while 1210 met the valley criteria. As points were found that met one of the sets of criteria (i.e., the point was either a peak point or a valley point) they were recorded with a separate incremental index. Thus, for this trial, there were 1256 peak points numbered 0-1255 while the valley points were recorded separately with an index of 0-1209. In the interest of simplicity, these values were sampled in index increments of 50 before being plotted here. However, in an actual weighing procedure, all values are averaged.

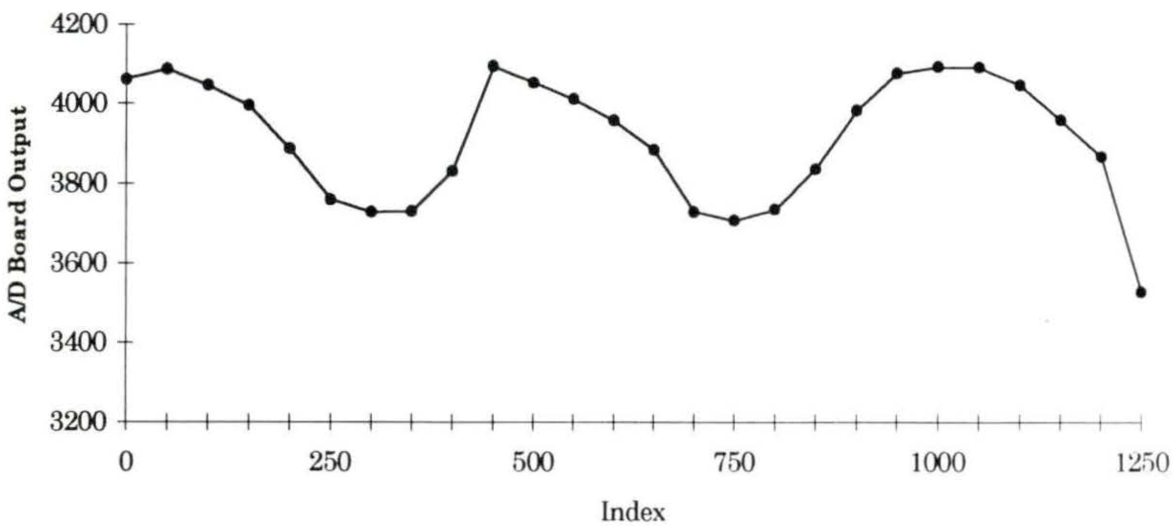


Figure 19. Graph of Peak Points Determined During Weighing Procedure

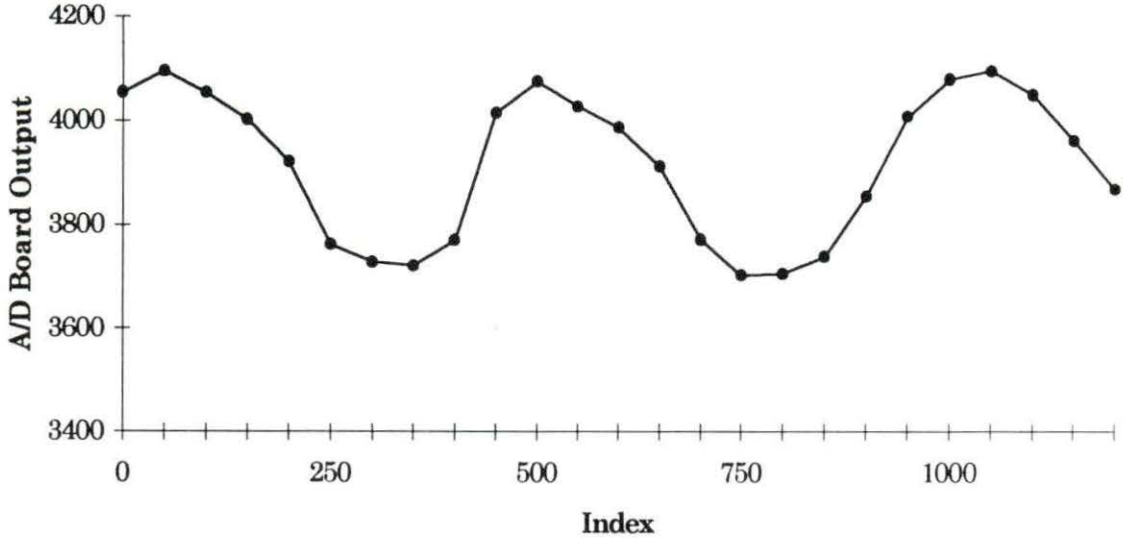


Figure 20. Graph of Valley Points Determined During Weighing Procedure

Figure 19 clearly shows three distinct sets of peak values. These are located at index 0-300, 300-750, and 750-1250. Similarly, Figure 20 shows two distinct sets of valley points (index 50-500 and 500-1050) and the beginning of a third (1050-1200).

Static Weight Testing

The results of the static weight testing are reported in Table 8. As previously described, ten trials were conducted on each of the known weights. Only the mean and standard deviation for each of these sets of trials are reported here. Furthermore, the difference between the system's determi-

Table 8. Results of Static Weight Testing

Known Weight		Determined Weight (pounds)		Difference
in grams	in pounds	Mean	Standard. Dev.	
0.0	0.0000	0.000	0.0000	0.000
934.6	2.060	2.037	0.0000	0.023
1554.6	3.427	3.410	0.0080	0.017
2269.3	5.003	4.983	0.0074	0.020
2802.3	6.178	6.157	0.0048	0.021
3286.5	7.246	7.227	0.0079	0.019
3641.2	8.028	8.006	0.0064	0.021
3891	8.578	8.564	0.0000	0.014
4524.3	9.974	9.964	0.0074	0.010
5132.4	11.315	11.326	0.0064	-0.011
5505.7	12.138	12.153	0.0064	-0.015
5885.9	12.976	12.997	0.0080	-0.021
6404.8	14.120	14.142	0.0064	-0.022
6895.6	15.202	15.231	0.0073	-0.029
7306.6	16.108	16.148	0.0048	-0.040
7712.4	17.030	17.047	0.0050	-0.044
8141.8	17.950	17.994	0.0000	-0.045
8413.7	18.549	18.602	0.0048	-0.053

nation of a weight and the determination of that same weight by the digital scale are listed under "Difference".

A scatter plot of the static weighing results is shown in Figure 21. These results show a high correlation between the known weight and the determined weight (r=.9999975) with a standard error of estimate at 0.013 pounds (14).

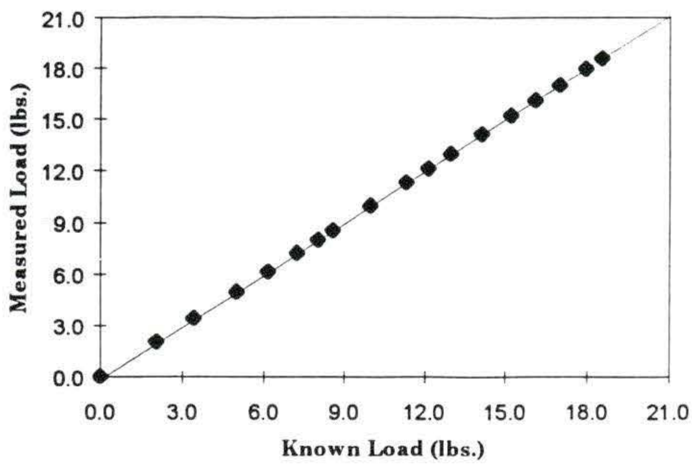


Figure 21. Scatter Plot of Static Results

In order to determine *HydroStats'* bias, precision, and uncertainty (at least for static weighing), the standard deviation and difference columns can be used. The first step is determining the mean and standard deviation of the difference column (using absolute values)-- these are found to be 0.0237 and 0.0131, respectively. Using Student's t method (10) (confidence of 95%), we see that the difference of the system's determination of a weight's value from the weight's true value (as determined by the digital scale), i.e., the system's bias, is somewhere in the range of 0.023±0.007, or 0.016 to 0.030. Thus, considering the worst case, we can say that for static weight determination, bias is 0.030 pounds.

In order to determine the precision of the system, we examine the standard deviation of determined weight column. The mean and standard deviation of this column are 0.0051 and 0.0029, respectively. Student's t results in a range of 0.0051±0.0014, or 0.0037 to 0.0065. Therefore, at worst, *HydroStats* is precise to 0.0065 pounds (95% confidence) in static weighing.

This precision result is somewhat confusing, however. The resolution of the system was calculated earlier to be only 0.015 pounds. This brings about the need for careful examination of the terms precision and resolution. The following is a direct excerpt from Beckwith et al., (10) (p. 53).

> *Precision* The difference between the instrument's reported values during repeated measurements of the same quantity. Typically this value is determined by analysis of repeated measurements.
>
> *Resolution* The smallest increment of change in the measured value that can be determined from the instrument's readout scale. The resolution is often on the same order as the precision; sometimes it is smaller.

While the system showed high precision as a result of repeated measurement, it is still limited by its resolution for any single measurement. Therefore, to say a single weight reading from *HydroStats* was good to 0.0065 pounds would be incorrect because a single measurement is limited to a resolution of 0.015 pounds.

In order to determine the uncertainty in the system's weight determination we must consider both bias and precision error. This is done by taking the square root of the sum of the squares of the two sources of error (10):

$$U_x = (B_x^2 + P_x^2)^{1/2}$$

$$U = (0.030^2 + 0.0065^2)^{1/2}$$

$$U = 0.0307$$

Thus, the uncertainty of a *HydroStats* determination of a static weight is 0.031 pounds (about 14 grams) over a range of 0 to 18.5 pounds.

By further analyzing the results, we can see much of the bias error occurs for weights greater than 15 pounds. Recall that the system uses a two point calibration system with the first point being 0 load and the second point being a known calibration weight. For these trials, the system was calibrated using a weight of 9.222 pounds. Thus, any results obtained that are greater than 9.222 pounds are based on an extrapolation of the calibration curve (Figure 17). By considering only weights of ten pounds or less (shifting the focus toward interpolated values) and repeating the statistical analysis just described, we arrive at an uncertainty of 0.023 pounds (about 10 grams).

Furthermore, the correlation of the known weight to the determined weight improves (r=.9999976) with a standard error of estimate at 0.008 pounds.

Static Simulation of Human Subject

The results of the static simulation of a human test subject are given in Table 9. As this experiment was meant to give only qualitative results through a small number of tests, no statistical analysis will be done. The column heading "Expected Weight" indicates the calculated underwater weight of the test system based on equation 10.

Table 9. Results of Static Simulation of Human Subject

Expected Weight (pounds)	Measured Weight (pounds)
2.957	2.787
4.766	4.727
3.009	2.853
1.422	1.261

Human Subjects Testing

The mean body fat determined for each subject as determined by *HydroStats* and its standard deviation are given in Table 10. These results are with n=5 trials for each subject. The quantity of interest here is the standard deviation of the trials, which is an indicator of the system's precision (see below).

Table 10. Body Fat Percentages of Human Subjects

Test Subject Number	Average Body Fat %	Standard Deviation
1	23.22	0.185
2	24.93	0.833
3	14.94	0.394
4	15.13	2.096
5	20.11	0.379
6	30.92	1.683
7	13.91	0.752
8	28.91	1.820
9	22.86	0.335
10	20.82	1.359
11	24.73	1.383
12	20.93	1.062
13	12.14	0.815
14	22.19	0.551

Statistical Determination of the System's Body Fat Precision

By further examining the standard deviation column of the table above, we can compute the precision of *HydroStats*. The mean value of the standard deviations is 0.875 with a standard deviation of 0.585. Calling the standard deviation of a single test subject's body fat percentage "d", and using Student's t method for a two-sided interval as a starting point, we proceed as follows with $\alpha = 0.05$ (confidence of 95%).

$$\bar{x} - t_{\alpha/2,v}\frac{S_x}{\sqrt{n}} < \mu < \bar{x} + t_{\alpha/2,v}\frac{S_x}{\sqrt{n}}$$

$$\bar{d} - t_{0.025,13}\frac{S_d}{\sqrt{14}} < p < \bar{d} - t_{0.025,13}\frac{S_d}{\sqrt{14}}$$

$$0.975 - 2.160\frac{0.585}{\sqrt{14}} < p < 0.975 + 2.160\frac{0.585}{\sqrt{14}}$$

$$0.975 - 0.338 < p < 0.975 + 0.338$$

Thus p=0.975 ±0.338 or alternatively, with 95% confidence, the precision of the system lies somewhere between 0.637 and 1.313 body fat percentage points. Therefore, by taking the worst possible case (with 95% confidence) we can say that the precision of *HydroStats* is about 1.3 body fat percentage points.

Re-examination of Precision Discounting Trials Involving Over-exhalation

A problem encountered was that all but four of the test subjects had at least one trial in which their wet VC actually exceeded their average dry VC. As previously described, this was not the behavior expected in the system's design. In order to determine whether "over-exhaling" contributed to loss of precision, the following table was made and a method was devised for discounting trials in which over-exhalation occurred.

As Table 11 shows, of fourteen subjects, ten had an over-exhalation in no more than two trials; of these ten, only one showed an increased standard

Table 11. Examination of Test Subject Over-exhalation

Test Subject Number	Trials with Over-exhalation	Standard Deviation. of Good Trials [a]	Standard. Deviation. of All Trials [a]	Difference (Improve-ment) [a]
1	1	0.226	0.185	-0.041
2	1	0.777	0.833	0.056
3	4	(N/A)	(N/A)	(N/A)
4	4	(N/A)	(N/A)	(N/A)
5	0	0.379	0.379	0.000
6	4	(N/A)	(N/A)	(N/A)
7	2	0.458	0.752	0.294
8	2	1.288	1.82	0.532
9	3	0.065	0.335	0.270
10	2	1.123	1.359	0.236
11	2	0.680	1.383	0.703
12	0	1.062	1.062	0.000
13	0	0.815	0.815	0.000
14	0	0.551	0.551	0.000

[a] Units are body fat percentage points

deviation in the trials having the expected incomplete exhalation (test subject 1). The mean value of standard deviation of the trials for the remaining nine subjects in which no more than two trials had over-exhalation (and improvement in the standard deviation occurred) is 0.793 with a standard deviation of 0.295. Using the Student t method with a confidence of 95%, the precision of *HydroStats* falls somewhere in the range of 0.793±0.295, or 0.622 to 0.963. By taking the worst case and rounding up, the precision of *HydroStats* improves to about 1.0 body fat percentage points when trials in which over-exhalation occurred are discounted (over 1.3 body fat percentage points when they are considered).

Comparison of Established Method to New Method

As described in the Materials and Methods section, all test subjects had their body fat percentage determined using both the established method (mechanical scale, operator estimation of wet weight, etc.) and the new method provided by this system. The results are compared in Table 12 and are plotted in Figure 22.

The correlation between the body fat percentages determined by the established and new methods when all trials are considered is 0.927 with a standard error of estimate at 2.17 body fat percentage points.

If a null hypothesis is defined to be that the established method and the new method are equivalent, Student's paired t-test yields the following results. The t-statistic is found to be 4.07 while the t-value for 13 degrees of freedom (two-tailed, $\alpha = 0.05$) is 2.160. As the t-statistic is greater than the t-value, the null hypothesis must be rejected (17). Furthermore, the p-value (the probability that the null hypothesis is true) is found to be only 0.0018.

Table 12. Comparison of %BF from Established and New Methods

Test Subject Number	Established Method (%BF)	New Method (%BF)[a]
1	20.19	23.22
2	20.25	24.93
3	11.78	14.94
4	14.76	15.13
5	18.40	20.11
6	27.09	30.92
7	10.63	13.91
8	28.14	28.91
9	23.26	22.86
10	15.06	20.85
11	21.31	24.73
12	18.78	20.93
13	13.91	12.13
14	21.58	22.19

[a] Average of all five trials

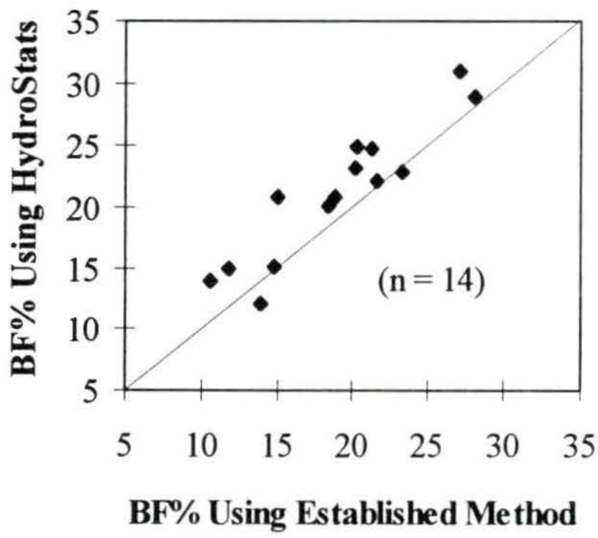


Figure 22. Scatter Plot of Human Subjects Results

Corrections

By making three corrections, the statistical comparison of the established method to the new method may be re-evaluated. These three corrections and their justifications are as follows.

Correction for Tube Buoyancy

The first correction made is for the buoyancy of the spirometer tube through which the test subjects exhaled during the procedure. As the submerged portion of this tube had a substantial volume (0.31 liters, assuming a submerged length of 2 feet with a diameter of 1 inch), this additional volume was added to the residual volume, gastrointestinal flatus volume, and incomplete exhalation volume in the determination of body density in order to correct for the tube's buoyant effect.

Over-exhalation Discounted

The second correction follows the reasoning outlined above under *Re-examination of Precision Discounting Trials Involving Over-exhalation*: five test subjects were eliminated from consideration due to over-exhalation. Of the remaining nine test subjects, only trials in which over-exhalation did not occur were considered.

Test Subject Discounted

The third and final correction begins with a careful examination of Table 12, which brings about suspicion as to the validity of the results of a particular test subject. Examining the differences between the results of the established and new methods, it is seen that the body fat percentage determined by the new method was always greater with the exception of test subject 13. The standard deviation of the difference in BF% between the two methods is found to be +1.31 while test subject 13 has a difference of -1.78. Thus the difference between the test subject in question and the standard deviation of all other test subject differences is 3.09 body fat percentage points, or 2.36 times the standard deviation of the differences of all other test subjects. While this does not meet the criterion of 3.0 standard deviations being the point at which a datum may be legitimately discounted, it certainly raises suspicion as to the validity of using the results of test subject 13. For the following analysis, the results of test subject 13 were discounted.

Re-Comparison of Established Method to New Method After Three Corrections

The results of the human subject testing after the three corrections just described are shown in Table 13 and are plotted in Figure 23. When the results are considered in light of the corrections, a correlation of 0.891 results. Furthermore, Student's paired t-test results in a t-statistic of 0.102 while the t-value for seven degrees of freedom (two-tailed, $\alpha = 0.05$) is 2.365. Thus, the null hypothesis previously stated cannot be rejected. Also, the p-value for this set of data is 0.926, indicating a strong probability that the old and new methods are equivalent.

Table 13. Re-comparison of %BF After Three Corrections

Test Subject Number	Established Method (%BF)	New Method (%BF)
1	20.19	23.23
2	20.25	24.64
3	(N/A) [a]	(N/A)
4	(N/A)	(N/A)
5	18.40	20.11
6	(N/A)	(N/A)
7	10.63	13.53
8	28.14	27.72
9	(N/A)	(N/A)
10	15.06	20.01
11	21.31	23.73
12	(N/A)	(N/A)
13	(N/A)	(N/A)
14	21.58	22.19

[a] (N/A) indicates test subject did not have at least three trials without over-exhaling or was test subject 13

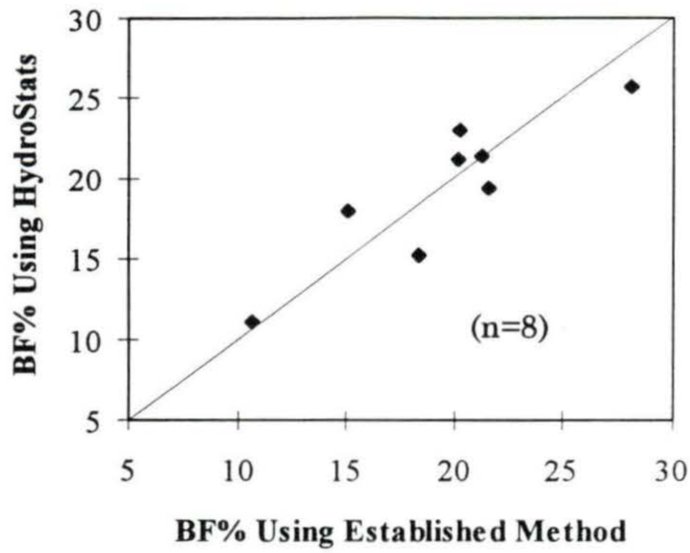


Figure 23. Scatter Plot of Corrected Human Subjects Results

Determination of System Uncertainty from Propagation of Component Instrument Uncertainty

A determination of *HydroStats*' uncertainty was also made using a direct analysis of the propagation of error through the following overall equation for body fat percentage (12), which is the Siri equation with substitutions made for body density, effective RV, and the Goldman-Becklake RV estimation.

$$BF\% = \left[\frac{4.950}{\left(\frac{W_a}{\left[\frac{W_a - W_w}{D_W} \right] - \left(0.017 * age + 0.06858 * height(in\ inches) - 3.477\right) - 0.100 - (VC_{dry} - VC_{wet})} \right)} - 4.500 \right] * 100$$

Thus, this determination of uncertainty is based solely on the uncertainties of the instruments used in the calculation of body fat during hydrostatic weighing. By using the characteristics of the "standard man" (15) and of the equipment used for these experiments, we can tabulate the quantities in the equation above with their uncertainties.

Table 14. Values Used in Propagation of Uncertainty Analysis

Quantity	Value	Uncertainty	Units
W_a	68.1	0.1	kg
W_w	2.93	0.03 [a]	kg
D_W	0.9937 [b]	0.0001	g/mL
Age	25	(N/A)	years
Height	68.00	0.25	inches
VC_{dry}	4.20	0.01	Liters
VC_{wet}	3.90 [c]	0.01	Liters

[a] Estimated by using 30g ≈ three times the uncertainty determined during static testing

[b] Assuming water temp of 36 °C

[c] Arbitrarily chosen

By calculating the propagation of uncertainty through the overall equation with these values, we arrive at an uncertainty for body fat percentage. This is accomplished in the following way. In the case of an addition or subtraction in the equation above, the uncertainty of the resulting sum (or difference) is computed by finding the squareroot of the sum of the squares of the uncertainties of the operands. In the case of a multiplication or division, the absolute uncertainties are first changed to relative uncertainties. The squareroot of the sum of the squares of the relative uncertainties is then the relative uncertainty of the multiplication or division. By repeating these two procedures throughout the equation, an overall absolute uncertainty of 1.3 body fat percentage points is found.

CONCLUSIONS AND DISCUSSION

General

The overall goal in the design of the system was to provide an improved automated method for determining body fat percentage using hydrostatic weighing. Specific goals were to provide a more accurate method for determining wet weight, an improved method for determining and correcting for incomplete exhalation, an easily operated user interface, and increased subject comfort during submersion. After being built, the system was tested successfully in a series of four static tests: A/D board function, sampling and averaging function, weight testing, and simulation of a human test subject. Fourteen human test subjects were tested using the established method as well as the new method with high correlation (r =0.891 to 0.927, depending on interpretation of results). On its own merit, the system had good precision (1.0 to 1.3 body fat percentage points, depending on interpretation of results).

Evaluation of Static Results

Static A/D Testing

As Table 7 clearly shows, the A/D board produces highly consistent results. Considering the resolution is 0.015 pounds (6.7 grams), and that the standard deviation of the A/D output in fifteen trials was only 0.46, it is highly unlikely that error in an A/D conversion could contribute in a significant way to the overall error of the system.

Static Weight Testing

The static weight testing demonstrated that the A/D board and load cell are capable of producing high precision and resolution under static conditions. While we have established that underwater weighing occurs with conditions that are far from static, with an uncertainty of 0.023 pounds (for static loads in the range of 0 to 10 pounds), at least it is known that the value produced by the A/D board for each of the ten thousand samples taken during a weighing procedure is highly accurate.

It can also be concluded that the system is most reliable in its determination of weight when the values being measured fall on the interpolated area of the calibration curve (uncertainty falls from 0.031 pounds to 0.023 pounds under these conditions). Therefore, it is best to calibrate the system such that the expected wet weight of a test subject is less than the calibration weight. By using a calibration weight of nine to ten pounds, this condition should be met for most test subjects.

Static Simulation of Human Test Subject

These results indicated qualitatively that the system was capable of meeting the results projected by calculation to within 0.17 pounds (or 77 grams). While this is not encouraging as compared to the high reliability of the static weight testing, it should be emphasized that the technique for calculation of expected weight involved several steps (introducing several opportunities for error) and that only four tests were conducted. Furthermore, as the test was conducted for qualitative results, the highest degree of accuracy was not pursued.

Sampling and Averaging Function

As Figure 19 and Figure 20 clearly show, the sampling and averaging function works as expected. These results are also qualitative in nature. While a complicated and more statistically intensive method for quantifying the accuracy of the function might have been pursued, this was not necessary in consideration of the following theory: with the total number of samples at ten thousand, a misidentified point which fell somewhere between a true peak or valley and to one side of the true average would be matched by another similarly misidentified point on the other side of the true average. Simply put, the sample is large enough to average out error. This also assumes that the operator initiates the procedure only when the test subject has completed exhalation, that the test subject is being as still as possible, and that the signal is approximately sinusoidal.

An interesting possibility for future research would be to test the averaging function with a vibrator or pendulum apparatus. Such a device would be capable of providing a sinusoidal perceived weight to the load cell. By weighing the apparatus first in a still state and then in a moving state, an evaluation of the averaging function's accuracy could be made.

Human Subjects Testing

The validation of the system using human subjects revealed encouraging results as well as opportunities for further refinement. Finding that the system yielded a precision of 1.0 body fat percentage points when the test subject had an incomplete exhalation (that is to say behaved as expected) was most encouraging. However, some important points should be made regarding this value. First, it is based on as little as three trials for a given subject and, secondly, it is based on the results of only nine subjects. Until further testing can be conducted, the overall precision of 1.3 body fat percentage points should be accepted as the precision of the system.

A probable cause for such a high percentage of the subjects "over-exhaling" while submerged in at least one trial of five is that the dry VC measurement was taken in a standing position while the wet VC was measured with the subject in a bent position at the end of the exhalation. This almost certainly caused a compressing effect which resulted in slightly more air being exhaled from the bent position. Therefore, for future testing, it is recommended that the dry VC measurements be made in a manner similar to that of the wet VC measurements: the test subject should be seated in an upright position, inhale completely, and then exhale through the spirometer tube as a forward bending motion is made.

The subject of the system's comparability to the old method is of interest. When all test subject trials were considered, correlation was high but the data failed Student's paired t-test. After making corrections, correlation decreased slightly while the data passed the t-test satisfactorily with a p-value of 0.926. Unfortunately, the latter results are with n=8. While these results are encouraging, further testing is clearly needed with corrections for tube buoyancy made ahead of time (as well as proper subject positioning during the dry VC determination, as just described). Testing of at least another fifteen test subjects would be desirable and this would allow a more definitive comparison of the old method versus the new method.

The topic of test subject discomfort and overall attitude toward the system is also of interest. While no scientific survey was conducted (which is a possibility for future research), it seemed to the author that nearly all the test subjects were pleased with the shortened time for weighing to occur over the established method in addition to the added security of a breathing tube. Furthermore, nearly all were interested in seeing their test results immediately after the procedure was complete. This would not have been possible with the established method.

Summary

This research indicates that an automated hydrostatic weighing system utilizing a load cell and making a correction for incomplete exhalation based on vital capacity measurements is viable. While the system would benefit from further refinement and validation, it has been shown here to be both accurate and reliable.

APPENDIX

Water Densities for Given Temperatures

Water Temperature (°C)	Density of water (g/mL)
15.0	0.91026
15.5	0.9990243
16.0	0.9989460
16.5	0.9988620
17.0	0.9987779
17.5	0.9986883
18.0	0.9985986
18.5	0.9985034
19.0	0.9984082
19.5	0.9983077
20.0	0.9982071
20.5	0.9981013
21.0	0.9979955
21.5	0.9978845
22.0	0.9977735
22.5	0.9976575
23.0	0.9975415
23.5	0.9974205
24.0	0.9972995
24.5	0.9971737
25.0	0.9970479
25.5	0.9695
26.0	0.9968
26.5	0.99665
27.0	0.9965
27.5	0.9964
28.0	0.9963
28.5	0.99615
29.0	0.9960
29.5	0.99585
30.0	0.9957
30.5	0.99555
31.0	0.9954
31.5	0.99525

Water Densities for Given Temperatures (cont.)

Water Temperature (°C)	Density of water (g/mL)
32.0	0.9951
32.5	0.9949
33.0	0.9947
33.5	0.99455
34.0	0.9944
34.5	0.99425
35.0	0.9941
35.5	0.9939
36.0	0.9937
36.5	0.99355
37.0	0.9934
37.5	0.9932
38.0	0.9930
38.5	0.9928
39.0	0.9926
39.5	0.9924
40.0	0.9922

REFERENCES

1. AKERS, R. and E. R. BUSKIRK. An underwater weighing system utilizing "force cube" transducers. *J. Appl. Physiol.* 26:649-652, 1969.

2. FAHEY, T. D. and R. SCHROEDER. A load cell for hydrostatic weighing. *Res Q.* 49:85-87, 1978.

3. MCCLENAGHAN, B. L. and L. ROCCHIO. Design and validation of an automated hydrostatic weighing system. *Med. Sci. Sports Exerc.* 18:479-484, 1986.

4. ORGAN, L. W., A. D. EKLUND, and J. D. LEDBETTER. An automated real time underwater weighing system. *Med. Sci. Sports Exerc.* 26:383-391, 1994.

5. BEHNKE, A. R., and J. H. WILMORE. *Evaluation and Regulation of Body Build and Composition.* Englewood Cliffs, NJ: Prentice Hall, 1974.

6. KEITHLEY METRABYTE CORP. *User Guide for the DAS-8, DAS-8PGA, & DAS-8/AO.* Taunton, MA: Keithley Metra Byte Corportation, 1990.

7. NILSSON, J. W. *Electric Circuits.* New York: Addison-Wesley, 1990.

8. MOTOROLA, INC. *FAST and LS TTL Data.* Phoenix: Motorola, Inc., 1985.

9. POLLOCK, M. L., and J. H. WILMORE. *Prescription for Programs of Prevention and Rehabilitation, 2nd ed.* Philadelphia: W. B. Saunders, 1990.

10. BECKWITH, T. G., R. D. MARANGONI, and J. H. LIENHARD V. *Mechanical Measurements.* New York: Addison-Wesley, 1993.

11. WEAST, R. C. (ed.), THE CHEMICAL RUBBER COMPANY. *Handbook of Chemistry and Physics, 54th ed.* Cleveland: The Chemical Rubber Co., 1967.

12. HARRIS, D. C. *Quantitative Chemical Analysis.* New York: Freeman, 1991.

13. LOHMAN, T. G. *Advances in Body Composition Assessment, Monograph Number 3.* Champaign, IL: Human Kinetics Publishers, 1992.

14. SPIEGEL, M. R. *Schaum's Outline Series: Theory and Problems of Probability and Statistics.* New York: McGraw-Hill, 1992.

15. SEAGRAVE, R. C. *Biomedical Applications of Heat and Mass Transfer.* Ames, IA: The Iowa State University Press, 1971.

16. GOLDMAN, K. I., and M. R. BECKLAKE. Respiratory function tests: normal values of medium altitudes and the prediction of normal results. *Am. Rev. Tuber. Respir. Dis.* 79:457-467, 1959.

17. FREUND, J. E., P. E. LIVERMORE, and I. MILLER. *Manual of Experimental Statistics.* Englewood Cliffs, NJ: Prentice-Hall, 1960.

18. SIRI, W. E. The gross composition of the body. In C. A. Tobias and J. H. Lawrence (Eds.), *Advances in Biological and Medical Physics.* 4:239-280, 1956.

19. BROZEK, J., F. GRANDE, J. T. ANDERSON, and A. KEMP. Densiometric analysis of body composition: Revision of some quantitative assumptions. *Annals of the New York Academy of Sciences.* 110:113-140, 1963.