Continuous Body Monitoring

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1 SenseWear: A Body Worn Sensor System

When a person who usually wears a watch forgets to put it on one day, it is common for them to look at their wrist anyway expecting the watch to be there. Without looking or touching to check, they are not aware of the watch's presence or lack thereof. The watch becomes a part of their expected experience due to its comfort and continuous utility. It satisfies Thad Starner's definition of a wearable system as "always with you, always on, and always accessible"[22]. At another end of the ambient intelligence spectrum the design vision of Stefano Marzano is one where the " 'relationship' between us and the technology around us will be of utmost importance. This relationship will no longer be one of user towards machine but of person towards 'object-become-subject', thus towards something that is capable of reacting, of being educated and responding [18]." Amongst the myriads of applications envisioned in an "ambient culture" by Stefano's team are the person, their clothing, their home and furniture, and an amenable outside world [17].

The interdisciplinary team at Bodymedia, Inc. designed the SenseWear armband in the realms of both Starner's and Marzano's ideals. SenseWear is a multi-sensor system designed for wearing in contact with the body 24 hours a day, 7 days a week, with periodic removal for hygiene. Figure 1 shows the SenseWear armband being worn. SenseWear is designed to continuously provide, record, and share information about the state of the wearer through nearly all of their life activities. The SenseWear armband is an active data collection point and "hub" of physiological and context based ambient information systems. Like the watch, it is "always with you, always on, and always accessible". What SenseWear does for you, because it's accessible, may not be continuously apparent. Accessibility to information mediated by the device is completely dependent on particular associated applications. SenseWear is often used as a continuous silent and unobtrusive activity monitor. It's worn and in contact with the skin continuously because it's doing something for you continuously. We regularly observe that SenseWear users forget they are wearing the device during normal use. Indeed on the occasions when a SenseWear user has their armband off they occasionally reach or feel for it, just like they might with a watch. In the wearable computing field this takes SenseWear into the realms of Mann's eudaemonic wearable [15].

The SenseWear armband performs continuous monitoring of the person 24/7 in an unobtrusive way and can communicate its findings wirelessly to other devices around it. This has clear benefits for ambient environments and information

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Fig. 1. The SenseWear PRO_2.

devices. The SenseWear Armband is commercially available from BodyMedia, Inc. based in Pittsburgh PA, as a research tool giving access to "raw" and derived data. Specifically configured SenseWear armbands, together with custom end-user software applications, are also commercially available from BodyMedia or their partners, for example the weight management system HealthWear available from Roche [21].

This chapter describes the armband's functionality and gives an overview of the technical capabilities of the armband and its construction. A breadth of applications are presented showing the feasibility and acceptance of a body worn continuous monitor. This illustrates the SenseWear armband's utility as an ambient intelligent device.

1.1 Why an Accessory and Not Apparel?

A study of suitable locations on the human body for both sensing physiology and locating hard components resulted in candidate locations and form factors for continuous body monitoring [7, 10] (See Fig. 2). The combination of sensors (discussed later) and the desired small unobtrusive form factor resulted in a decision to have multiple sensors and data collection inside a single unit worn on the triceps.

SenseWear occupies a body region that is new for skin-touching wearables – the upper arm. A custom stretch elastic was employed, the bottom of the unit and sensors conformed to maximize contact, and thousands of hours of testing performed to achieve a design that was comfortable and "completely forgettable" on vastly different arm sizes. A major achievement in this process was developing a design that was tight enough to keep the sensors in place against the arm without slipping, but loose enough not to constrict the user's arm and cause discomfort – a sensitive balance.

Flexible, symmetrical wings were developed to stabilize the device on the arm (ensuring good sensor contact) and molded to a circumference exactly between

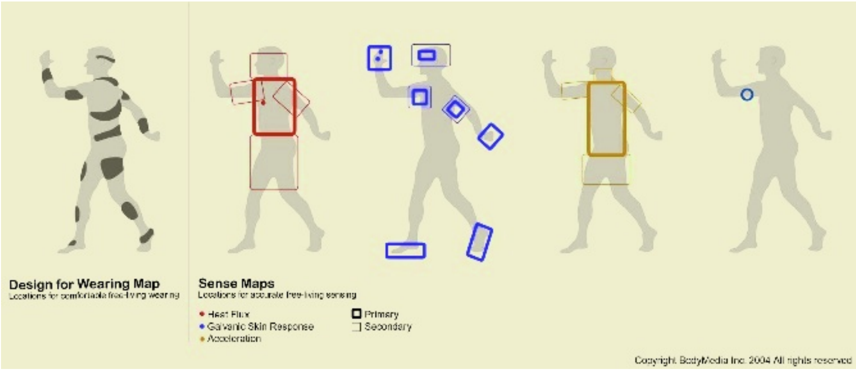

Fig. 2. Shapes and positions from the original "Design for Wearability" study [7], far left. To the right of this are four visualizations reflecting subsequent research in 1999. These highlight sensor locations for heat flux, galvanic skin response, and acceleration. The SenseWear armband location is identified far right.

the smallest and largest adult arm sizes. They fold inward to fit the smallest adult female arm (down to 203mm/8" circumference) and expand to accommodate the arms of large bodybuilders (up to 622mm/24.5" circumference) making the system usable by virtually all adults.

SenseWear is made from molded plastics and surgical grade stainless steel, materials approved in the USA for skin contact. The unit is easily cleaned. In home use the unit might be wiped clean when washing one's self. In a clinical setting the strap is changed and unit cleaned between subjects. The strap is made from nylon, polyester, and polyisoprene (no latex) in three sizes: small, one size fits most, and large. Specifically, the straps fit 140mm/5.5" – 241mm/9.5", 203mm/8.5" – 432mm/17" and 406mm/16" – 622mm/24.5" arm circumferences. By being readily cleanable, the sensor component is suitable for almost 24/7 wearing. When a user bathes they take it off with their clothes, replacing the clothes and the armband at the same time. The straps are detachable for washing. The suggested wearing duration is 23 hours in any 24 hour period.

The armband is minimally invasive. Furthermore, it is comfortable and invisible for most observers even if the user is wearing a short sleeved shirt. It is in skin contact, but only at the surface, and is thus less intimidating or uncomfortable than semi-invasive sensor devices such as some blood-glucose meters, or clinical heart rate monitors where electrodes are adhered to the skin. Completely invasive sensors such as implants have a certain positive unobtrusiveness and 24/7 monitoring capabilities. An example of such a device is an implanted loop recorder for cardiac care. However, by comparison, the process of implantation is extremely expensive, and carries a substantial psychological barrier for broad consumer use.

1.2 Real Time Versus Post Activity Analysis

The SenseWear armband is a ubiquitous computing device, however it is not always used as a real time device. Indeed for applications such as clinical study and clinical weight management SenseWear is usually used as a passive continuous data gatherer. The data is analyzed after the fact. In the weight management setting for example, a user may wear the armband all day, simply going about their business. Importantly, the armband does not restrict the user, but is simply constantly collecting data about them and their activity. At the end of each day, for example, the user retrieves the data to another system such as a PC where the data is analyzed and acted upon. In the clinical setting, experimenters can deploy subjects with SenseWear and have it collect data outside the lab for up to fourteen days. The subjects may keep diaries as well, but SenseWear is an objective observer, providing automatic journaling of the wearer's activities and body states. At the end of a study SenseWear provides a data set for the experimenter to manipulate in numerous ways not possible in real time. Many examples of SenseWear in real-life use are given later in this chapter.

Real-time data becomes more important for reactive ubiquitous devices and environments. In these cases, SenseWear is equipped with a short-range transceiver and can communicate with similarly equipped devices. SenseWear units are uniquely addressable. The transceiver is currently commercially available in additional sensory products such as weight-scales. In this case the user stands on the scale, and their weight is transmitted to the armband, where it is inserted into the data stream.

2 Architecture and System

SenseWear is a tool – a body worn, wearer focused, sensor and data hub that can perform an application on its own, or be part of a much more extensive system. Two generic frameworks are presented: stand-alone and supervised.

2.1 Supervised

Figure 3 illustrates SenseWear's place in a large-scale system. There is no specific application in this particular system view. All components are information systems, thus are customizable to specific applications. This particular system architecture illustration considers numerous SenseWear users wearing the armband and being constantly monitored. Elsewhere, connected by the internet, clinicians, care givers, fitness professionals or other concerned parties monitor the wearers after the raw sensor data has been analyzed. The Apex fitness system (described in Sec. 5) is an example of this architecture deployed commercially.

2.2 Stand Alone

A stand-alone system, with optional home PC support would have an architecture shown in Fig. 4. Third party devices can log their sensor readings or other pertinent information amongst the continuous armband data by using the transceiver kit. SenseWear research customers also can add the transceiver to their own devices.

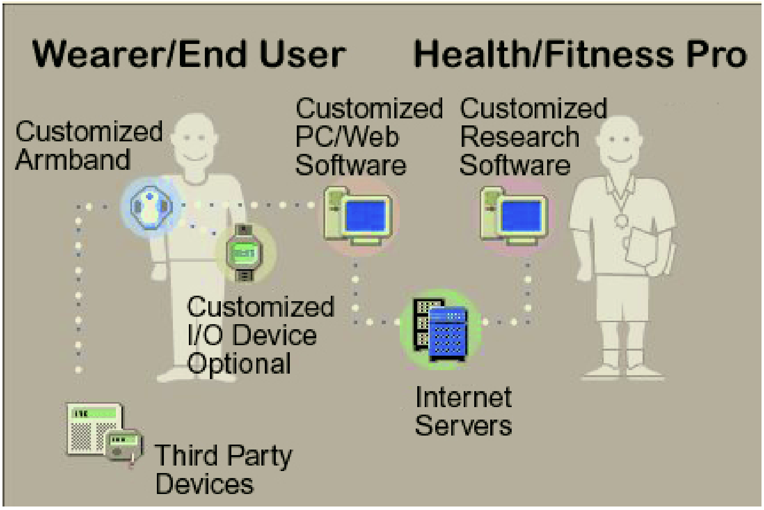

Fig. 3. Illustration of information communicated between SenseWear users and professional advisors.

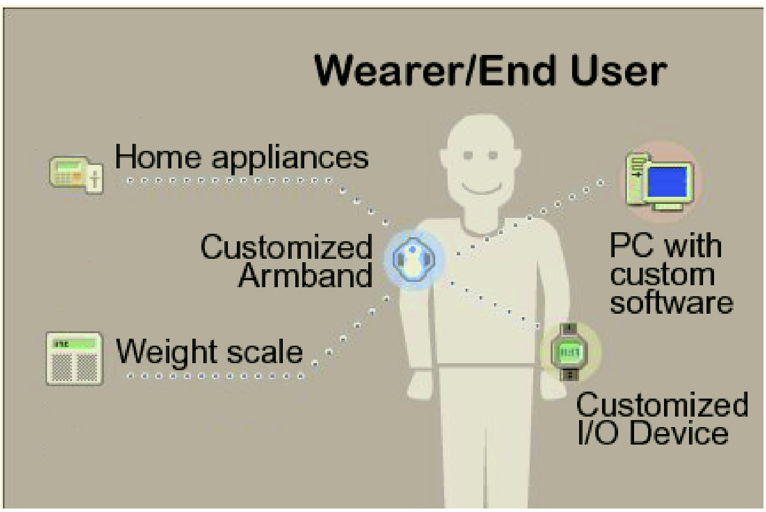

Fig. 4. A stand-alone home system architecture.

These architectures are realizable and in some circumstances already commercially deployed through the use of some modular components. On Microsoft Windows PC's there are both stand alone applications for accessing SenseWear data and internet transport mechanisms. A programmable transceiver kit allows for custom third party devices to communicate their data to the armband. Software systems exist for professionals to manage and view the data of their users remotely.

3 The SenseWear Armband – Specifications

The SenseWear armband is comfortable to wear, can be worn continuously, and will store up to 14 days of physiological data before the data needs to be retrieved. The armband is also equipped with wireless capability for retrieving the stored data and also for providing real-time feedback. The specifications in Table 1 are for SenseWear II.

3.1 Sensor Detail

The following provides more detail about the sensors in the Bodymedia armband. Specifically the 2004 model SenseWear Pro_2. After the physical sensors are characterized we will consider why the important thing is not what is being sensed, but what can be detected. For example, one can not purchase a pedometer sensor, a calorie-burn sensor, nor a sleeping sensor. Yet these are what SenseWear ultimately monitors and reports. From the physical sensors are derived synthetic sensors, contextual information, and other measures [2].

Accelerometer. The accelerometer is a 2-axis MEMS device that measures motion. The motion can be mapped to forces exerted on the body and the gravity information can provide valuable context information for predictive algorithms. The accelerometer has a resolution of approximately 0.005g and is presently calibrated to match a reference gravity of one g to within 0.05g on the longitudinal axis, 0.06g on the transverse axis. The axes are relative to an upright armband, longitudinal being from ground to sky and transverse parallel to the ground. Worn on the back of the upper arm, transverse is through the chest.

Heat Flux. The proprietary heat flux sensor is a robust and reliable device that measures the amount of heat being dissipated by the body at the location of the armband. The sensor uses materials with very low thermal resistance and extremely sensitive thermisters. It is placed in a thermally conductive path between the skin and the side of the armband exposed to the environment (see Fig. 5). A high gain internal amplifier is used to increase the resolution of the measurements to a resolution of < 0.3 W/m^2. The accuracy of the heat flux sensor is tested in a wide range of temperatures, with a low inter armband variability about room temperature. At two regions of particular interest, the heat flux sensor has a resolution of 0.267 W/m^2 in thermal equilibrium at 22°C (room temperature); and a resolution of 0.291 W/m^2 at 50 W/m^2 heat flux at 32°C (skin temperature). The high gain amplification results in a very sensitive instrument, highly suited to higher rate sampling.

Galvanic Skin Response. Galvanic skin response (GSR) represents electrical conductivity between two points on the wearer's arm. The GSR sensor in the armband includes two hypoallergenic stainless steel electrodes integrated into the underside of the armband connected to a circuit that measures the skin's conductivity between these two electrodes (see Fig. 5). Skin conductivity is affected by the sweat from physical activity and by emotional stimuli. GSR is used as an

Table 1. Detailed specifications for the SenseWear II armband.

Dimensions and weight
(l) 85.3mm x (w) 53.4mm x (h) 19.5mm. Weight 85g.
(l) 3.4" x (w) 2.1" x (h) 0.8". Weight 3.0 oz
Mechanical
Medical Device Grade ABS – monitor top and skin-touching bottom.
UV-stabilized Thermoplastic Urethane(TPU) – flexible wings, overmolded to monitor top.
FDA-registered co-polyester – skin touching label covers screws providing a smooth interface to skin.
Surgical grade stainless steel 304 – external sensors, progressive stamped and insert molded to bottom.
Custom designed non-latex elastic – adjustable strap.
Hardware
Battery – 1 AAA, up to 14 days continuous use (24/7).
Memory – 512Kbytes of flash data storage, up to 14 days continuous use (24/7) in standard configuration.
Processor – low power 16 bit w/integral program flash, scratch RAM, A/D, and peripheral support.
USB – USB 2.0 interface with drivers for Windows 98, ME, 2000, and XP.
Wireless – ISM band 916.5MHz radio transceiver for wireless communication.
Sensors
Accelerometer – 2-axis MEMs device
Heat Flux – patented configuration of injection molded heat pipe, sensor, and differential amplification
Galvanic skin response – symmetrical stainless steel pads insert molded into the ABS bottom
Skin temperature – thermistor-based sensor assemblies

indicator of evaporative heat loss by identifying the onset, peak and recovery of maximal sweat rates. The GSR circuit records skin resistance to a high degree of accuracy over a wide range of values, with a 2.5nSiemen maximum error up to 100nSiemens, and a 2.5% maximum error otherwise. Typically minute averages in GSR show small changes from minute to minute. Subtle physiological effects can be seen in GSR at higher sampling rates.

Skin Temperature. Skin temperature is measured using a highly accurate thermistor-based sensor located on the backside of the armband near its edges and in contact with the skin. Continuously measured skin temperature is approximately linearly reflective of the body's core temperature. The skin temperature sensor has a resolution < 0.05 degrees Celsius and is accurate to 0.5°C

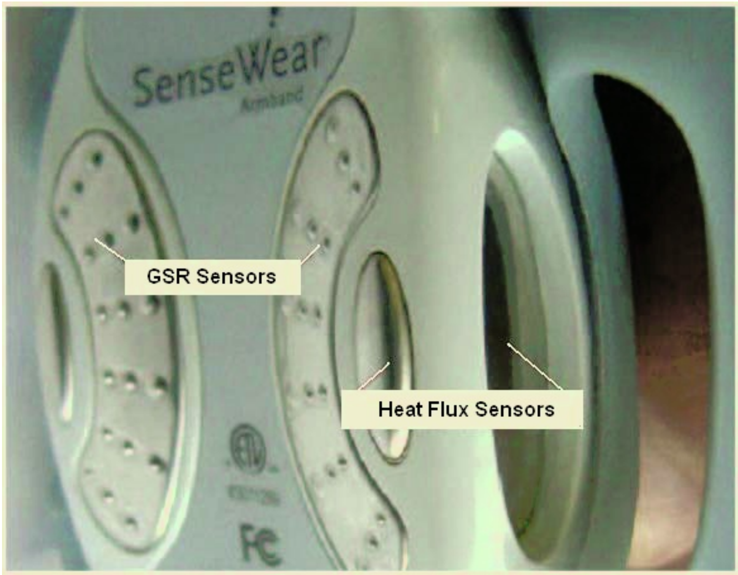

Fig. 5. Sensor positions on the back and side of SenseWear. The GSR sensors are a pair positioned on the underside of the unit, in contact with the skin. The heat flux sensor has a skin contact component on the underside and a cover component on the side of the unit.

between the 20 and 40 °C range (68°F-104°F). At room temperature the resolution is 0.02°C. Typically minute averages in temperature show small changes from minute to minute. Subtle physiological effects can be seen in temperature at higher sampling rates. The temperature sensor is recording the skin temperature, thus changes in the local thermal environment can also cause this reading to change indirectly by causing changes in skin temperature.

3.2 Derived Measures – Synthetic Sensors

The SenseWear armband samples all of the raw sensors at 32 Hz. From these signals, many other signals are calculated and derived. In many SenseWear systems a set of derived channels are then recorded at a much lower rate, such as once per minute. These synthetic sensors can include simple metrics such as averages and summations, but can also include complex computations such as activity classification and energy expenditure. In SenseWear systems these synthetic sensors appear as additional sensor data streams.

Energy Expenditure (EE). The medical standard for measuring caloric expenditure is the VO2 metabolic cart. But these machines tend to be large, lab-restricted devices that require a technician's supervision. The SenseWear armband was designed to provide results comparable to a metabolic cart but in a small wearable form factor, invisible to observers, usable in a free-living environment, easier to put on and as comfortable as a wristwatch (see Fig. 6).

Fig. 6. VO2 metabolic cart in a lab setting.

The energy expenditure algorithm in the SenseWear system is multi-sensory. There are limitations to single-sensor products (e.g. pedometers, accelerometers) in deriving calorie expenditure. Such products are capable of seeing only one or two-dimensional activities and can not differentiate between the myriad activities performed throughout the day. The SenseWear system is a tested and proved first-of-its-kind multi-sensory design that can intelligently recognize contexts and apply the appropriate sensors to measure the activity being performed. This innovation not only improves accuracy, but in applications such as HealthWear allows the system to communicate the contexts (activities) that are most effective for achieving the wearer's weight loss goals.

BodyMedia has already developed software that integrates the signals from the sensors in the SenseWear armband and processes them using algorithms that provide estimates of energy expenditure during different types of physical activity. Energy Expenditure, often calculated in units of metabolic equivalents (METS) for exercise physiologists, is a size and weight independent measure of calories burned. Energy expenditure is predicted by first classifying the data into an activity class (e.g., ambulatory exercise, biking-like exercise, other exercise, or resting). An appropriate regression equation is then applied. The classifiers and equations were tuned on indirect calorimetry data collected from subjects performing the relevant activities (see Fig. 6).

Pedometer. An onboard algorithm in the armband calculates steps based upon the high rate two-axis acceleration data stream.

Wearer's Context. Many SenseWear systems can predict when the wearer is in a number of standard states, including lying down, sleeping, being restful, traveling in a moving vehicle, walking, running, biking, and other types of exercising. These categorizations can be important for other algorithms (e.g. energy expenditure) or in their own right, depending on the particular application. For example these classifications can be used to automatically record a person's activities during a day – in other words, auto-journaling. Another application is simply to record the amount of exercise or rest that a person undertakes in the course of wearing the armband.

Future Sensors. While not available as commercial products in 2004, there are additional applications and capabilities that make sense for the SenseWear platform.

Heart rate is a prime physiological indicator and an active area of research and development at BodyMedia with a goal of recording heart rate as comfortably and as unobtrusively as the SenseWear armband measures sleep, activity, and energy expenditure. Other areas of research and development include algorithm and software support for diabetes management, hydration monitoring, and sleep. All these are applicable for monitoring in the home and free-living environments rather than in the clinic.

3.3 System Embodiments

The SenseWear armband is currently commercially deployed in three different packages: research, weight management, and fitness.

The research and clinical system is a stand-alone system comprised of armbands and research software. The software allows for the initialization, sampling rate configuration, data retrieval, and viewing of collected data from the armbands. The research software gives the user a great deal of control over their armband and the collected data compared to the other applications. The raw data, and many of the derived measures such as sleep and energy expenditure are exportable as Microsoft Excel or comma separated value files for further analysis. HealthWear is the brand name of the clinical weight management package available from Roche. This combines the armband with a web site-based tracking system designed to be used in the context of a clinical setting, allowing individuals to monitor their progress from home PCs. The Apex Club Based Weight Manager is a managed fitness system available from the Apex Fitness Group that combines the armband with a personal training regimen and a web site-based meal and exercise planning and tracking system. Both these systems are now described in more detail.

4 Roche HealthWear

> *"The percent of persons who are overweight or obese (BMI of 25 or higher) increased from 56% in 1988 to 64% in 1999-2000 [23]."*.

> *"With obesity on the rise, we can expect a sharp increase in diabetes rates to continue. Unless these dangerous trends are halted, the impact on our nation's health and medical care costs will be overwhelming."* Jeffrey P. Koplan, MD. Director, US Centers for Disease Control and Prevention 1998-2002 [12].

HealthWear[1] is an innovative and educational weight loss system consisting of a small wearable monitor (the HealthWear armband), a user friendly internet application (HealthWear Weight Center) and algorithms to provide wearers with the most accurate calorie balance system available. The HealthWear Armband uses a collection of sensors to gather personalized physiological data from the wearer. This information is downloaded to the Weight Center where algorithms

Fig. 7. This figure shows the overall view of HealthWear Weight Center, with charted weight and calorie balance.

[1] HealthWear is a trademark of a Member of the Roche Group. ©Roche Diagnostics.

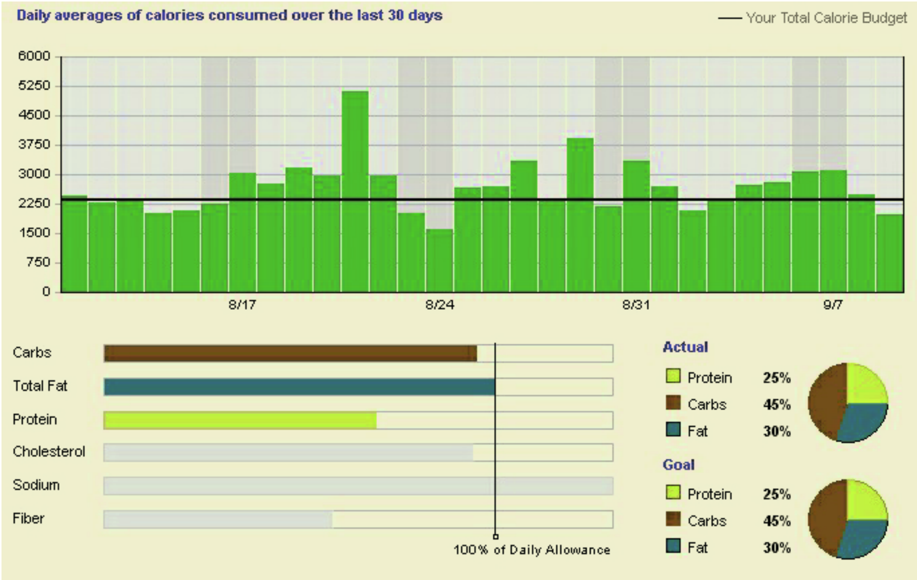

Fig. 8. This figure shows the thirty day summary of calories consumed and nutrition. The users' energy consumption daily goal is shown as 2260 calories. Below the consumption graph is a break down of their actual food intake against their goal.

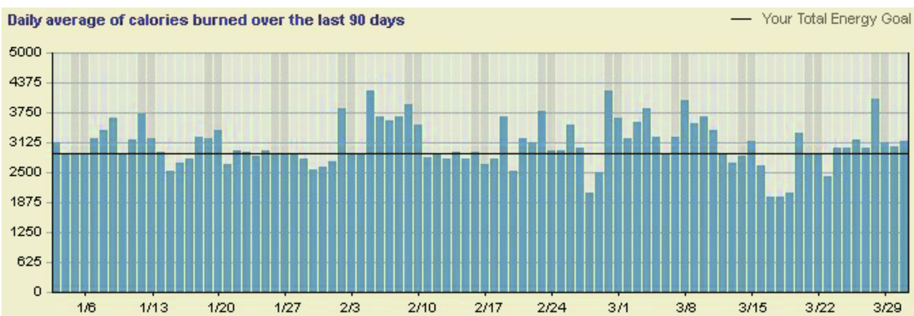

Fig. 9. This figure shows a ninety day summary of energy expenditure. The horizontal black bar is the user's goal energy expenditure, one vertical bar per day, the darker vertical lines indicate weekends. users can look for lifestyle patterns over time.

translate the wearer's data into accurate caloric expenditure feedback. Together with the wearer's nutritional intake which is entered in the Weight Center software, the system records, trends, and presents the user's calories burned, calories consumed, and the balance between the two; information that is critical when trying to lose weight, but never previously available outside the laboratory.

A calorie deficit is required if one is to lose weight. However, tracking calories consumed is difficult and accurately counting calories burned has been virtually impossible outside of a clinical environment (see Fig. 6).

Fig. 10. The HealthWear armband. Back view, right, is without strap.

The HealthWear System automatically records and tracks calories burned. Tracking calories consumed is enhanced with an innovative online food diary. The system goes one step further to compare the data, report the results, and recommend to the user ways in which to reach their personal weight goals. Screenshots from the HealthWear application are shown in Figs. 7, 8 and 9.

From a technology perspective, HealthWear is both a medical device and wearable computer – two product categories often equated with technology-centric complexity. To reduce this perception, the team created a goal to take the best parts of these product categories: the accuracy implied in medical devices and leading-edge technology implied in wearable computers, and blend them into a new form and interaction experience that conveys empowerment and health. A highly ergonomic and body shaped form factor, integrated and seamless material transitions achieved through over and insert-molding, and soft, light colors help convey this perceptual message (see Fig. 10).

The HealthWear armband has only one button, which is used to view the memory and battery status. All other interactions are automated, increasing simplicity, reducing user error and reinforcing the advanced nature of the device.

The HealthWear armband turns on simply by sliding it on. Once the armband detects that it is being worn, the armband turns on. A short vibration and friendly sound sequence indicate that the armband is starting to monitor. When the wearer slides the armband off, it turns off.

Uploading the data stored on the armband to the HealthWear website is just as easy. While wearing the armband the user opens the Weight Center software and transmits their information through a small Wireless Communicator connected to the user's PC USB port. This device is a disk 65mm in diameter, domed to 20mm at the center and 4mm at the edge.

By reducing the size of the technology and enabling the system with online software, HealthWear liberates clinically accurate weight monitoring from the lab, allowing patients to proactively monitor their goals in a free-living fashion, see their progress in the context of everyday living, predict their weight loss or gain trend, and share results with their health care provider. The HealthWear

System allows for easy recording, tracking, and reporting of critical information required in the weight-loss battle, but never before available in a non-clinical setting.

5 Apex Club Based Weight Manager

> *"BodyMedia has developed a device that, properly integrated into a weight control program, has the potential to turn the tide on obesity."* (Neal Spruce, CEO of Apex Fitness Group).

The Apex[2] Club Based Weight Manager provides fitness professionals and their clients with a highly accurate, easy-to-use solution for establishing and managing fitness and weight loss goals. The system tracks caloric intake and expenditure automatically, without the requirement of food logging. The system is supported by other features such as a state-of-the-art food menu generation engine and comprehensive reporting features for both fitness professionals and club members. Figure 11 shows the armband at use in the Apex program.

Apex Fitness specified this software system to take advantage of the continuous energy expenditure and context monitoring capabilities of SenseWear. The Apex web-based Weight Manager is deployed in clubs around the USA. For a club member this involves using a software system together with a fitness professional, and the option of wearing "the sleek wearable body monitor." The web-based nutrition and coaching software helps club members and their personal trainers establish and keep track of fitness and weight loss goals. The armband gives objective measures of energy expenditure during fitness sessions and during the rest of the day.

Apex programs are well established over the last twenty years, and are the most widely available fitness programs in the USA. 24-Hour Fitness is the leading health club chain in North America. This broad and timely experience is employed through a (human) supervised system architecture.

The inclusion of continuous energy expenditure monitoring enhances the weight control programs by informing the client about exactly how much food they can consume before they store it in all the wrong places. This is a calorie-counting program where users do not need to do anything other than wear the device and weigh themselves once a week. The fitness professional combines their experience, their knowledge of the client, and the recorded armband data to better advise the client.

One of the many functions of the BodyMedia armband is the ability to accurately measure a person's total calories burned in any timeframe, allowing the wearer to view the result and adjust their food intake accordingly. The ability to monitor total energy expenditure, together with the trainer's ability to accurately measure body mass changes, allows the system to report back to each user and their fitness professional what the user's total calorie intake has averaged without any manual recording. The system reports estimated food intake (calories in) and measured energy output (calories out).

[2] Apex is a trademark of the Apex Fitness Group.

Fig. 11. This figure shows armbands worn in the gym and a user with a fitness professional discussing the client's recorded results.

The Apex Club Based Weight Manager is personalized according to the user's eating and exercise preferences. The Apex program, using the guidelines of the American Dietetic Association, creates an individual program for each user according to their particular food likes and dislikes. As a result, Apex program participants are more likely to achieve a sustainable weight loss change.

6 SenseWear Everywhere

> *"My subjects like the Armband because they don't really notice they are wearing it. It's an exciting technology that combines physiological and activity monitoring information."* Dr. Scott J. Strath, Ph.D. Research Fellow. Ann Arbor VA Hospital.

Researchers from a variety of fields have used the SenseWear Armband and InnerView Research Software (IRS versions 1.0-4.0) in various investigations.

In most cases researchers were willing to share their data and analysis, which has helped BodyMedia to continually improve both the SenseWear armband and the research software, to strengthen user and activity data pools, and to improve BodyMedia's ability to train, choose, and develop more sophisticated algorithms.

Often, research specialists provide the first instance of focused group data (e.g. obese, diabetic, cardiac and pulmonary subjects) affording unique opportunities to realize previously undiscovered physiological information that can lead to better understanding of typical and distinctive qualities in the data characteristics of a group or activity set. We expect this cyclical exchange to continue, improving the accuracy and scope of BodyMedia tools in both research and diagnostic settings.

The SenseWear Armband is particularly interesting as a data collection device for medical applications because it allows data collection in free-living environments without using cumbersome or invasive laboratory equipment (see for example Fig. 6). Similarly, SenseWear is a useful tool for studying psychosocial situations because of its noninvasive, constant, multisensor data logging capabilities. This can enhance qualitative field notes with physiological information overlays and, in some situations, reduce or eliminate note taking by hand. Furthermore, with data streaming technologies in place, SenseWear provides the potential for remote information collection, analysis, and synthesis.

6.1 Energy Expenditure and Exercise Physiology

Researchers have used BodyMedia Armbands in a variety of clinical studies often in relation to energy expenditure and fitness studies. University of Pittsburgh has collaborated with BodyMedia on a number of research initiatives including energy expenditure, sleep, and eating disorders. Dr. Kupfer, Chief of Behavioral Medicine at UPMC sees the armbands and associated software as an opportunity to "get information... we could previously get only in a lab" and sees great potential for using armbands for affordable public health studies.

Jakicic et al [9] and Fruin et al [6] tested the SenseWear PRO Armband against indirect calorimetry measurements for energy expenditure during rest and during use of multiple fitness machines such as treadmills and stationary bicycles. The Jakacic study [9] found "When exercise specific algorithms are used, the SenseWear Pro Armband provides an accurate estimate of energy expenditure when compared to indirect calorimetry during exercise periods examined in this study." The Fruin study [6] found "The SWA provided valid and reliable estimates of EE at rest and generated similar mean estimates of EE as IC on the ergometer; however, individual error was large. The SWA overestimated the EE of flat walking and underestimated inclined walking EE."

King et al [11] studied multiple activity monitors including CSA, TriTrac-R3D, RT3, BioTrainer-Pro accelerometers, and the SenseWear Armband. Their study concluded that "The CSA was the best estimate of total EE at walking and jogging speeds, the TriTrac-R3D was the best estimate of total EE at running speeds, and the SenseWear Armband was the best estimate of total EE at most speeds."

Chronic Obstructive Pulmonary Disease (COPD) physiopathologists at the University of Pittsburgh have found wearable body monitoring (WBM) devices useful for research, stating that for therapy study "exercise tests have gained popularity as outcome measures . . . [acting as] surrogates of 'free-living' activity, which. . . may represent the more meaningful outcome [20]." This group tested a portable telemetric breath-by-breath (EE-BXB) metabolic device against the BodyMedia SenseWear armband on COPD subjects concluding "A WBM is a reproducible and valid measure of physical activity in the laboratory setting and should, therefore, be a valid measure of 'free-living' activity and a highly meaningful outcome measure in COPD clinical trials [20]."

Other researchers are taking advantage of free-living information gathering capabilities for estimating energy expenditure, for example Cole et al[3].

Researchers at Virginia Tech are using BodyMedia armbands to monitor activity levels of human participants involved in diet and exercise studies concerning conjugated linoleic acid (CLA), a substance found to increase metabolic rates and decrease fats in lab rodents.

Health Management Consultants of Virginia are developing a children's game aimed at encouraging lifestyle changes based on activity levels – in this case footsteps recorded during a day. Children are given the choice to wear a SenseWear armband that automatically retrieves to the game or a pedometer with a parent controlled, daily log. Children's footsteps equal points necessary to continue game play, which gives an advantage to the armband option because of more frequent data updates. Preliminary feedback indicates decreased TV watching and increased footsteps in child subjects.

6.2 Telemedicine

One of the largest commercial markets in America is that of the "aging" baby boomer. There are projected shortages of health care professionals to tend to the future needs of this large socioeconomic group as well as a greater emphasis on quality of life issues. Remote medical monitoring is one answer to this growing need. It allows fewer health care professionals to diagnose and care for more patients at greater distances saving money, spreading the breadth of specialized expertise and allowing for patients to have more autonomy and a perceived higher quality of life by spending more time at home and less time in a hospital.

Along with remote medical monitoring capabilities for home health comes health monitoring capabilities for more dire situations.

Sandia National Laboratories, of Lockheed Martin Company, has included BodyMedia armbands in its survey of body monitoring systems with potential to support telemedicine for both military and social health initiatives.

Researchers at the Department of Computer Science, University of Central Florida find that a barrier to tele-health is the attenuation of information exchange between a health care provider and a remotely located patient. To improve communication, they are developing emotional maps derived in part from physiological data points collected by SenseWear armbands to help get "objective indicators of patients' emotional status in a useful form to enhance patient care [14]."

CERMUSA is an applied research and technology center located on the campus of Saint Francis University in Loretto, PA. They are working with Bodymedia in the field of monitoring technologies for patients in remote areas suffering from chronic diabetes and obesity. As part of this project, clinical researchers will use the SenseWear system together with wirelessly enabled glucose meters and weight scales to remotely monitor vital patient information such as blood-glucose levels, exercise habits, sleep quality, weight change, nutritional intake and overall compliance with programs administered by their caregiver.

6.3 Industry and the Work Place

Worker health, satisfaction, and productivity greatly effect manufacturing facilities fiscal gains. Better understanding worker stress, workload, and bottlenecks will provide the potential to improve training, working conditions, and work flow, increasing efficiency, safety, and yield.

PPG Industries, conducted a study to investigate whether differences in automation effected worker fatigue and effectiveness. Dr. Colombi, Corporate Medical Director for Environment, Health and Safety at PPG Industries, used BodyMedia armbands to measure workers' energy expenditure over shifts in two different facilities. He found "that the SenseWear armband accurately measured the levels of activity and amount of energy expended by the 40 plant workers who participated in the study" and further concluded "A wearable energy dosimeter is a viable alternative to oxygen consumption and heart frequency to evaluate workload assessment [4]."

ARUP, an architecture engineering and design firm, whose well known buildings include the Sydney Opera House, investigates the environmental conditions of its buildings for comfort. The company uses physiological data collected from BodyMedia armbands to better understand design performance in free-living situations [24].

NASA with the National Bio-Computation Center is investigating the potential for using SenseWear technology to monitor astronaut's health in space and during training.

6.4 Human Computer Interaction

Researchers from the Human Computer Interaction Department, Carnegie Mellon University used the armband to study comfort perceptions of wearable technology. Participants were given an armband or a hydration device and told the device served social, medical, or regulatory functions. Researchers noted that "significant differences in desirability and comfort ratings were found between functional conditions, indicating that functionality is a factor of comfort [1]."

6.5 Human Interaction

Not one person can be expert in all that is necessary, for instance, to bring a product to market; individuals are trained mostly in their field of expertise and not in collaborative work. To successfully work as a team it is helpful to be more aware of individual and team dynamics so participants can act progressively toward goals.

Sandia Collaborative Working [5], used BodyMedia armbands while it "explored the potential for real-time signal analysis to provide information that enables emergent and desirable group behavior and improved task performance" by mapping audio, video, physiological, and somatic data of test subjects playing a collaborative game. The group used an array of sensors, processors, and software to develop a tool that can identify individual and group trends, identify their states, and give warnings and help in decision-making [19]. This pointed to individual and group stress and efficiency trends useful for studying future group work situations.

Nasoz et al [16] looked at the ability to predict emotions from physiological information taken from SenseWear PRO_2 armbands while watching emotionally scored movie clips. "The affective intelligent user interfaces we plan to create will adapt to user affect dynamically in the current context, thus providing enhanced social presence." The team predicts that machines that identify and modify output based on users' emotions can optimize teaching, improve emotional communication between remote users, and suggest modifications to unsafe emotions in particular contexts.

A multi-university team used the BodyMedia armbands to detect whether a user is busy or not busy in order to determine interruptibility. "Our motivation is derived from the observation that context does not require a descriptive label to be used for adaptivity and contextually sensitive response. This makes an approach towards completely unsupervised learning feasible [13]." This investigation was a preliminary step towards making devices subservient to their users instead of the typical, opposite reality.

7 Application, Capability, and Acceptance

BodyMedia armbands and software are useful devices for comfortably collecting body measurements, which can lead to better understanding and detection of the user's physiological and emotional states, improved progress checking and training, and data collection in situations requiring high mobility. When coupled with environmental information or data from user groups, information can lead to better design of physical environments.

Contextual aware devices can calculate situation appropriate responses that may greatly change future context-specific human computer interaction and information feedback loops, leading to beneficial changes in education, health, work and leisure.

The SenseWear continuous body monitor is presently mainly deployed in health and fitness domains. Currently available are consumer products, professionally supervised products and scientific and social research products. The data from SenseWear remains a largely untapped diamond mine. At the 2004 International Conference on Machine Learning eight workshop papers discussed the process of discovering new information in a SenseWear data set of 64,000 multi-sensor samples. Topics included discovering if the wearer was watching television and identifying the gender of the wearer [8].

SenseWear is mostly worn as an everyday health and fitness diagnostic tool. However, SenseWear has also been used in out-of-the-ordinary situations and by extraordinary people. Armbands have been used while training guards in a mock prison riot and by airport fire fighters. SenseWear has gone up Mt. Everest, traveled to both the North and South Poles, and has been around the world on a yacht – all to better understand human physiology in extreme environments and situations. In the field of sports, the armband helps athletes better understand their bodies. Armbands have been worn by marathon runners, a super welterweight boxing champion, a Wimbledon tennis champion, and a basketball Hall of Famer. SenseWear wearers include three gold medal Olympians.

SenseWear has been described as "a dashboard for your body." Wearing the armband has high value because it tells you objective information about yourself, at a very low personal cost. Measures such as hydration and fatigue can be indicated when they are difficult to impartially self observe. The fuel efficiency notion of miles-per-gallon can be transferred into human terms of caloric efficiency. With unobtrusive, noninvasive, continuous body monitoring, other ambient intelligent devices have the opportunity to know you better.

Sensing silently
Data doesn't know its worth
My ubiquity

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