ACTIGRAPH AND ACTICAL PHYSICAL ACTIVITY MONITORS: A PEEK UNDER THE HOOD

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Running Head- Electro-mechanical properties of two common activity monitors

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Abstract

The use of accelerometer based activity monitors (AAM) is getting increasingly popular among physical activity (PA) researchers. The technology of AAMs is rapidly evolving. For example, changes are continuously being made to monitor hardware [type of sensor (piezoelectric, piezoresistive, capacitive, etc.) and output format (counts *vs.* raw signal)]. Commonly used AAMs belong to the ActiGraph AAM family (7164, GT1M, and GT3X) and the Actical (Phillips Respironics). This article accumulates and presents information on several basic electro-mechanical aspects of these activity monitors. A majority of this article focuses on the evolution of the ActiGraph AAM, i.e., describe the differences among the 7164, the GT1M, and the GT3X models. This is followed by brief descriptions of variable monitor characteristics attributable to device firmware and the calibration status of these monitors. A smaller part of the article is dedicated to the Actical because this device has not undergone any major changes since it was first introduced.

The information in this article may be useful to researchers in gaining a better understanding of the functioning of these AAMs. Additionally, this information could also help researchers to describe these monitors more accurately in scientific publications. For example, a common misconception among several PA researchers is that the ActiGraph GT1M and GT3X are piezoelectric sensor based AAMs.

Introduction

Paragraph number 1.Since the early 1900s, accelerometers have been used to measure vibrations and detect motion in various industrial applications (2-4). Based on the idea that quantitative knowledge of the force acting on the human body during dynamic movement provides a comprehensive description of any physiological phenomenon, Cavagna, Saibene, and Margaria (1961) developed one of the first accelerometer-based activity monitors (AAM) (1). As compared to strain-gauge accelerometers used by Cavagna et al. (1961), in the 1980s, AAMs with technologically advanced piezoelectric ceramic sensors were introduced in the field of objective monitoring of physical activity (PA). (4). Since then, AAMs have gained prominence in PA measurement and currently there are several commercially available AAMs. In addition to piezoelectric sensors, current AAMs are also based on piezoresistive and capacitive technology. Commonly used AAMs are those manufactured by ActiGraph, (Pensacola, FL.), (i.e., the 7164, the GT1M, and the GT3X) and Phillips Respironics (Bend, OR.) (the Actical). This article provides brief descriptions of specific 'electro-mechanical' aspects of the ActiGraph and Actical monitors that may help researchers further their understanding of these AAMs. Although PA researchers can obtain the information provided in this article from various open/closed sources, this article assimilates these facts to provide a freely available single source for several important features of the ActiGraph and the Actical.

The Actigraph AAMs

AM 7164

Paragraph number 2. When the AM7164 was introduced, ActiGraph described it as an electronic device that was a combination of many different parts and pieces. Unlike several currently available AAMs, the AM7164 does not contain a micromachined Microelectro-Mechanical-System (MEMS) accelerometer. The acceleration sensor in the AM7164 is a bimorph piezoelectric cantilever beam that has a seismic mass attached on one end, while the opposite end of the beam is mounted on the electronic circuit board of the device. The bimorph beam comprises of two mechanically bonded, synthetic lead zirconate titanate crystals. In response to acceleration, the seismic mass causes the sensor to bend and resonate in a direction parallel to the acceleration and produces a proportional electric charge. This analog electrical charge is filtered using a hardware-based (multiple semiconductor components) band-pass filter and then digitized by an 8-bit analog-to-digital convertor (ADC). The signal also undergoes full-wave rectification; i.e., conversion to absolute acceleration values. The filtered, digitized, and full-wave rectified acceleration signals are then converted to activity counts.

GT1M and GT3X

Paragraph number 3. The AM7164 was subsequently replaced by the GT1M in the mid 2000's. ActiGraph stated that the GT1M was more cost-effective and had upgraded technology while providing similar output to its predecessor. The main difference between the AM7164 and the GT1M is that the former has a piezoelectric sensor that detects dynamic accelerations (resulting from motion), while the GT1M uses a capacitive accelerometer capable of detecting both static (for e.g., force of gravity detected when stationary) and dynamic accelerations. Unlike piezoelectric accelerometers where a change in acceleration results in the production of a proportional electric charge, a capacitive accelerometer detects change in acceleration through changes in capacitance of the sensing element; in other words, variations in the sensor's electric charge storage potential.

Paragraph number 4. The acceleration sensor in the GT1M is the ADXL320 (Analog Devices, Norwood, MA), which is a 4 x 4 x 1.45 mm surface micro-machined, monolithic integrated circuit chip (polysilicon), dual-axis MEMS accelerometer. The ADXL320 has a full-scale range of $\pm$ 5*g* and measures both static and dynamic accelerations. However, ActiGraph specified restrictions allow the detection of only those accelerations that lie between 0.05 to 2 *g*. Structurally, this capacitive accelerometer has two independent polysilicon fixed plates that act as electrodes, and between the two fixed plates is a parallel movable central plate. This plate is movable because it is suspended as a bridge structure using polysilicon springs that are attached to the sides of the structure. The suspended central plate forms two back to back capacitors with each fixed plate on either side. In other words, the three plates form a differential capacitor where the deflection of the central plate in response to acceleration causes a change in the capacitance of the two back to back capacitors. The change in capacitance causes specific voltage changes to the existing electric flow, which is an analog signal that is proportional to the detected acceleration. This low voltage signal is first amplified using an amplifier and is then digitized, rectified, and the direction/s (vertical, antero-posterior, and medio-lateral axes) of the acceleration are determined using a 12-bit ADC (sampling rate= 30 Hz.) and phase demodulation techniques. Finally, the signal is filtered at a bandwidth of 0.25 to 2.5 Hz. This means that the acceleration signal is markedly attenuated if the frequency of acceleration peaks falls outside this range. ActiGraph's rationale for using a band-pass filter is that most forms of human movement fall within this frequency range, and the filter might be useful for eliminating high-frequency artifact vibrations.

Paragraph number 5. In mid-2009, ActiGraph released the GT3X containing the ADXL335 accelerometer (Analog Devices, Norwood MA.). The ADXL335 is a 4 x 4 x 1.45 mm triaxial capacitive MEMS sensor with a full scale range of $\pm$ 3*g*. The structure and theory of operation of the ADXL335 is similar to that of the ADXL320. Other than the accelerometer in the GT3X, all other specifications including the filter and the ADC are precisely the same as in the GT1M. Additionally, although both the GT1M and the GT3X have the capability to measure static accelerations, only the GT3X provides inclinometer output. The GT3X uses vector magnitude data from all three axes and assigns a number from 0 to 3 to distinguish whether an individual is not wearing the monitor (number 0), is standing (number 1), lying (number 2), and sitting (number 3).

ActiGraph pre-filtered 'Raw-Mode'

Paragraph number 6. Unlike the AM7164, both the GT1M and the GT3X also provide output in the pre-filtered 'raw- mode.' This is an important feature in the two capacitive AAMs because the general consensus at the conference in July 2009 entitled "Objective Measurement of PA: Best Practices and Future Directions" was to begin using raw accelerations instead of activity counts while measuring PA. Prior to April 2010, the output in the pre-filtered 'raw mode' was a representation of the analog-to-digital quantization of accelerations sampled every 0.033 s (sampling frequency of 30 Hz.) by the accelerometer. The analog-to-digital quantization values are discrete, unsigned digital numbers proportional to the voltage signal generated by the accelerometer in response to acceleration. Firmware modifications in April 2010 changed the output in the pre-filtered 'raw mode' to represent the actual *g*-force sampled every 0.033 s. To provide researchers with a better understanding of output in the raw-mode, the following section of the paper explains the calculations involved in obtaining the two aforementioned 'raw-mode' variables.

Paragraph number 7. The analog-to-digital quantization is calculated using several parameters including the sensitivity of the ADXL320/335 accelerometers (174 millivolts/*g* for each axis), the total number of levels in which a sampled acceleration can be classified (12-bit analog to digital converter enables 4096 (2^{12}) different levels), and the zero *g* offset of 1.5 V. The 4096 levels of the 12 bit ADC is spread equally across a 3 V reference voltage. Therefore, each ADC step is equivalent to 732.4 µV. Taking into account the zero-*g* offset of 1.5 V, the voltage signal when the accelerometer detects an acceleration of + 3 g would be 2.022 V ([3 *g* * 0.174 V/*g*] + 1.5 V). Therefore, the pre-filtered 'raw-mode' output equals 2760 [(2.022 x 1000 x 1000) µV÷ 732.4 µV]. The 'raw-mode' output in *g* force units (e.g., 3 *g*) is obtained in the following manner: 2.022 V (voltage signal from accelerometer) – 1.5 V (zero-*g* offset) ÷ 174 millvolts/*g* (sensitivity of accelerometer)

Paragraph number 8. Although the ADXL320 and the ADXL335 originally have unequal sensitivities of 174 millivolts/*g* and 270 millivolts/*g*, respectively, ActiGraph states that the sensitivity of the GT3X accelerometer is scaled to match that of the GT1M to ensure comparability in output. However, it is unclear if a GT1M initialized in the pre-filtered 'raw-mode' will measure a higher range of accelerations (-5 to +5*g*) than the GT3X, which only measures accelerations in the range of -3 to +3 g. If this is the case, the output from the GT1M and GT3X in pre-filtered raw mode will not be similar to each other. Output in the post-filtered 'raw-mode' is not a representation of the actual raw acceleration signal because it is subjected to transformation associated with manufacturer specifications (for example-band-pass filtering).

Firmware Updates

Paragraph number 9. Firmware is defined as a software programming code containing a set of instructions that enable communication between the hardware components of a device. The firmware in the GT1M and the GT3X is stored on the onboard ‘flash read-only-memory’ and it performs several functions including filtering of the accelerometer signals. In comparison, this function in the AM7164 was performed by hardware components. Since the firmware is stored within flash memory in the GT1M and the GT3X, it can be erased and replaced with updated versions. ‘Scheduled’ firmware releases by ActiGraph usually coincide with improvements that are made to the devices. For example, firmware version 03.01.01 for the GT3X was a ‘scheduled release’ containing added support for the new 16 Mb memory devices. Similarly, firmware release 04.01.00 in July-08 for the GT1M enabled users to measure accelerations in the antero-posterior axis in addition to the vertical axis. On the other hand, ‘unscheduled’ firmware releases are also made when ‘bugs’ (e.g., an issue that causes inaccuracy of output) are identified and need to be fixed. A potential ‘bug’ we observed in our lab was the presence of significant differences among activity counts in the antero-posterior axis from the GT3X and the GT1M (firmware 04.01.00) at different walking and running speeds (unpublished observation). This problem was particularly evident at the speed that marked the transition from walking to running (unpublished observation). A subsequent firmware release for the GT1M resolved this likely ‘bug’ by restoring the similarity in antero-posterior axis activity counts during walking and running between the two AAMs.

Paragraph number 10. Although susceptible to programming errors, an advantage of having a firmware-based system is the reduction in possible errors due to the loss of calibration. As compared to the firmware filter in the GT1M and the GT3X, the drift and tolerance characteristics of each of the multiple semiconductor components in the AM7164 hardware filter contribute to the possibility of a loss in calibration. ActiGraph states that the GT1M and the GT3X do not require calibration. However, in our lab we have observed that the GT1M and the GT3X can lose calibration (unpublished observation). Researchers are encouraged to use the option available in the ActiLife software that allows one to confirm calibration of the GT1M and the GT3X.

Paragraph number 11. Since the GT1M and the GT3X are used to measure PA, a possible way for these AAMs to lose calibration is from exposure to impact forces (e.g., being dropped). Several capacitive accelerometer manufacturers strongly caution against dropping the accelerometer onto hard surfaces and also furnish 'drop-test' details in the technical specifications. Even though the electronics of the GT1M and GT3X are enclosed in a hard polycarbonate plastic casing, we were curious to determine if dropping a calibrated GT1M on a hard surface would cause the ADXL accelerometer within to lose calibration. To answer this question, we dropped a calibrated GT1M a few times on a concrete floor from a height of approximately 2.0 m. We selected this height because we were not aware of the ADXL320 accelerometer's 'absolute maximum rating' for a 'drop test,' and the height of 1.8 m was the 'absolute maximum rating' height for a similar capacitive accelerometer that we use in our lab. Dropping a GT1M from this height did not cause the GT1M to lose calibration. However, we cannot comment if calibration is compromised due to repeated exposure to similar forces.

Next Generation ActiGraph GT3X

Paragraph number 12. Actigraph is currently developing the next generation GT3X, which will be physically smaller and have a greater data storage capacity (256 MB) than the current GT3X (16 MB). Additionally, this device will be water submersible, thereby enabling the recording of water based activities like swimming. The accelerometer in the next generation GT3X model can detect accelerations ranging between $\pm$ 8 *g*. This AAM will collect activity data in the 'raw-mode' only and provides researchers with the flexibility of selecting one of ten different data sampling rates ranging from 10 to 100 Hz in multiples of 10 Hz (i.e., 10 Hz., 20 Hz., 30 Hz., etc.). This AAM will be released and made available during the latter half of the 2010.

The Actical AAM

Paragraph number 13. The Actical is a 37 x 29 x 9 mm omni-directional AAM. The accelerometer in the Actical is the solid-state *muRata Piezotite*® (Kyoto, Japan) PKGS-LD-R series sensor. The sensor is a 6.4 x 2.8 x 1.2 mm ceramic package, which encloses a rectangular bimorph lead zirconate titanate   piezoelectric element. Although the Actical has a bimorph piezoelectric sensor like the AM7164, there is a distinct difference in how the two sensors in these devices detect accelerations. The sensor in the AM7164 uses a seismic mass cantilever beam mechanism. On the other hand, the sensor in the Actical AAM is surface mounted on the PCB and does not have a seismic mass mounted at one end of the bimorph piezoelectric element. In the Actical, vibrations in response to accelerations are transferred from the ceramic enclosure of the sensor to the piezoelectric element, thereby deforming the sensor and resulting in the production of a proportional charge. Although the sensor is omni-directional, it is positioned within the Actical in such a way that when it is worn on the hip, the AAM is most sensitive to vertical accelerations. The voltage generated by the sensor is amplified and filtered (0.5 to 3.0 Hz.) by analog circuitry and then digitized by an analog to digital converter at a sampling frequency of 32 Hz. In contrast to the ActiGraph GT1M and GT3X, the Actical does not provide the flexibility of providing 'raw-mode' data or in any time-epoch lower than 15 s. However, Phillips Respironics will be launching a new Actical AAM, which can provide output in 1-sec epochs and has increased memory capacity (256 kb).

Future of AAMs

Paragraph number 14. Currently, the field of objective monitoring of PA is still in its formative years. However, the introduction of AAMs has provided PA researchers with reasonably accurate and reliable monitors, as well as preliminary methods to estimate PA and energy expenditure in the free-living environment. Currently, scientists are working on developing novel PA monitors that measure accelerations at multiple locations on the body and also measure other physiological variables (e.g., respiratory rate and volume). Some researchers are also working on incorporating AAMs in to everyday devices like cellular phones. Additionally, advanced energy expenditure estimation (using AAM output) techniques such as Artificial-Neural-Networks and Classification Tree Modeling are being utilized. The introduction of superior data processing methods and improved wearable activity monitors will help to advance the field of activity monitoring.

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References

1. Cavagna G, Saibene F, and Margaria R. A three-directional accelerometer for analyzing body movements. *J Appl Physiol*. 1961;16:191.
2. Karcher J. A piezo electric method for the instantaneous measurement of high pressures. *Journal of the Franklin Institute*. 1922;194(6):815-6.
3. Walter P. The history of the accelerometer. *Sound and Vibration*. 1997;31(3):16-23.
4. Wong TC, Webster JG, Montoye HJ, and Washburn R. Portable accelerometer device for measuring human energy expenditure. *IEEE Trans Biomed Eng*. 1981;28(6):467-71.