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Aliasing affects ActiLife software raw accelerometry to count conversion from different sampling frequencies

M Garnotel, C Simon and S Bonnet, *Member, IEEE*

***Abstract*—Accelerometry counts are widely used to quantify physical activity in an objective manner. ActiGraph™ accelerometers offer to record acceleration signal with different sampling frequency (fs). Nevertheless additional counts were shown to be computed by ActiLife software from acceleration signal with a sampling frequency fs>30 Hz compared to signal with default fs=30 Hz or multiple. This paper relies on the study of synthetic signals to point out the origin of this error and to recommend an adjusted method. A piecewise-frequency sinus time series (0-15 Hz) was generated at different sampling frequencies (fs=30, 50 and 100 Hz). The artificial acceleration raw signal was resampled to 30 Hz using different antialiasing lowpass filters before ActiLife count computation. The use of an antialiasing filter which did not properly attenuate aliasing replicas was found to induce aliasing frequencies within ActiLife bandpass filter which is the cause of extract activity counts. We were able to reproduce fictitious counts for acceleration around 10 Hz. A simple adjustment of antialiasing filter parameters allowed to avoid this problem. This study reproduces ActiLife counts processing from 50 and 100 Hz sampled signal. Count overestimations from fs=50 and 100 Hz signal were induced because of aliasing in the frequency bandwidth of the ActiLife count filter. This can be corrected by a relevant antialiasing filtering before ActiLife software processing or this can be done in high-level mathematical programing.**

***Clinical Relevance*— This study allows a correct interpretation of accelerometry counts when using different system's sampling frequency.**

I. Introduction

Since the 1980s, accelerometry has been widely used to objectively capture human physical activity (PA) spectrum. This method keeps going to be particularly promising due to technological progress relying on sensor miniaturization and new analytic advancements. The main challenge is to get human movement representative features from raw acceleration measured by accelerometer. Historically, accelerometry count, as a mirror of PA intensity, has been the main unit used in PA studies field. ActiLife software provides proprietary tools to calculate accelerometry counts from raw signal collected by the ActiGraph™ (ActiGraph Ltd, Pensacola, FL, USA), the most used accelerometer in epidemiological studies [1]. At accelerometry research timescale, ActiLife count processing has a long history relying on step-by-step processing improvement as ActiGraph material capability evolved. The AM7164 initial ActiGraph accelerometer model allowed uniaxial 10 Hz sampling frequency (fs) data collection within a 0.05–2.13 g dynamic range with signal processing realized at monitor level to generate accelerometry count. The last generations of ActiGraph are now triaxial with wider dynamic ranges (GT3X: ± 6g; wGT3XBT: ± 8g). Increased storage capacities allowed raw data collection from different fs (30 to 100 Hz). Processing procedure adaptations were thus required (e.g. resampling, filter parameters …) and were integrated in the data analysis ActiLife software according to technological advancement [2]. Limits were pointed out concerning the nonlinear relation between count and PA intensity, such as a count plateau phenomenon during high intensity activity [3] and count overestimation according to fs choice during the same PA [4]. Despite some information provided by the manufacturer, the opacity of proprietary software disallowed researchers to explain the origin of those anomalies and to fully interpret results based on accelerometry count. Raw-to-count processing chain was only very recently decrypted in order to give full-interpretation keys to the community [5]. The methodology developed in [5] allowed replication of count computed from ActiGraph accelerometer with default 30 Hz fs and highlighted the impact of bandpass filter during high intensity activities, explaining the count plateau phenomenon issue. Nevertheless, this methodology was not validated for 50 and 100 Hz sampled data which have been shown to induce count overestimation compared to 30 Hz default fs [4].

Although ActiLife software is proprietary and the exact lowpass filters parameters used remain unknown, two major elements support an issue related to an incorrect downsampling when using a fs of 50 or 100 Hz. The first one is that count overestimation with a fs of 100 Hz was observed compared to 30 Hz even with an identical acceleration energy into artificially generated input file. The second is the lack of additional count when using multiple of the 30 Hz default fs (i.e. 60 or 90 Hz) while the use of other fs produced additional counts [6]. John et al. suggest that one possible cause could be an antialiasing filtering dysfunction during analog to digital conversion [7]. Nevertheless, count overestimation observed at 100 Hz compared to 30 Hz, while no amplitude differences, was reported between 30 Hz and 100 Hz raw signal suggests a post analog-to-digital conversion issue, probably occurring during the raw-to-count conversion itself. As ActiLife software code is not published, at our knowledge the possible reasons remain unexplored beyond theoretical discussions [4].

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M. Garnotel and C. Simon work with CARMEN, INSERM U1060/University of Lyon/INRA U1235, CRNH-Rhône-Alpes, Hospices Civils de Lyon, Lyon, France. Pavillon 1H–RdC 165 chemin du Grand Revoyet 69310 Pierre-Bénite, France. S. Bonnet works with CEA LETI MINATEC, University of Grenoble Alpes, Grenoble, France. 17 Avenue des Martyrs 38000 Grenoble, France. Corresponding author e-mail: stephane.bonnet@cea.fr

This study aims to put the light on a limitation of counts analysis by establishing pattern of raw-to-count conversion across the different fs. This issue is particularly of interest because a growing number of studies rely on signal with a fs higher than 30 Hz to keep the maximum of information from raw acceleration. Understanding the origin of the overestimation and how to overcome it appears to be crucial to allow comparison with previous published studies relying on activity count.

II. Material and Methods

Analyses were performed with MATLAB R2019b (The Mathworks, Natick, MA, USA).

A. *Artificial ActiGraph file generation*

In order to explore the whole range of human activity spectrum a frequency-sweep was generated with MATLAB at different fs (30, 50 and 100 Hz). The sinus frequency was increased every 30s in a piecewise manner from 0 Hz to 15 Hz with a frequency resolution of 33.4 mHz. Shannon criterion was fulfilled for each generated dataset. The total duration represented 450*30=13,500 seconds. The time series was then converted in MATLAB into a binary ActiGraph file (.gt3x) that was fed into the ActiLife software. Doing this, the same acceleration signal was processed and only the fs differed between files.

B. *Resampling*

A digital rate conversion (i.e resampling) was performed to produce acceleration signals that would have been obtained at fs=30 Hz before applying the count computation algorithm on the resampled time series.

Two simple boxcar antialiasing filters were evaluated with length (m) of 5 and of 6 to compare the effect of frequency attenuation on the count computation.

In the 50 Hz case, the resampling involved an upsampling to 150 Hz (by a factor of p=3) followed by a downsampling to 30 Hz (by a factor of q=5). Upsampling by a factor of 3 consisted in inserting two zeros between each sinus sample and then lowpass filter the signal to replace the inserted zeros. Downsampling by a factor of 5 consisted first in applying a lowpass filter to prevent aliasing and then decimate the signal, i.e. keep one sample every 5 samples. Lowpass filters are crucial in these operations and aliasing would occur if filter specifications were not met. The 100 Hz case followed the same line (i.e. p=3, q=10).

C. *Count Computation*

Two approaches were used for count computation 1) counts were computed directly in ActiLife software or 2) counts were computed in MATLAB using the approach developed in [5]. The acceleration signal, sampled at 30 Hz, was first band-pass filtered, and a non-linear function was applied to the rectified filtered signal. The resulting count was the accumulation of the transformed signal over a time window duration specified by the user. Counts were computed per 30-second windows. Details of count computations may be found in [5].

III. Results

The Fig. 1 illustrates the behavior of ActiLife software in case of pure sinusoidal accelerations sweep (0-15 Hz) generated with varying fs. ActiLife activity counts per 30s (cp30s) were found to be rigorously identical up to 5 Hz whatever the sampling frequency. The pattern reflects the nature of the bandpass filter involved in the count computation [5]. An aliasing of the spectrum was observed around 10 Hz for sampling frequencies equal to 50 and 100 Hz leading to a count overestimation for those fs compared to default 30 Hz sampling frequency. It represents an overestimation of 60% at 100 Hz and 20% at 50 Hz (cutoff at 5 Hz).

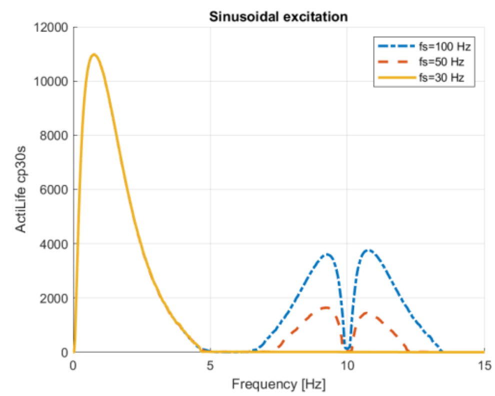

Figure 1. Count computed by ActiLife software from three frequency-sweep sinus (0 to 15 Hz) time series generated at different sampling frequencies. Yellow line: Input signal with a sampling frequency of 30 Hz; Orange line: Input signal with a sampling frequency of 50 Hz; Blue line: Input signal with a sampling frequency of 100 Hz.

Briefly here is a reminder of the aliasing effect observed when using resampling procedures at frequency that are not a multiple of the initial fs. To gain understanding on the behavior observed in Fig. 1, we give next a possible explanation in the context of a pure 8-Hz acceleration signal. As observed in Fig. 1, nonzero counts are associated with this frequency when fs is not a multiple of 30 Hz. Consider first the case of fs=50Hz. Upsampling (by a factor 3) creates signal replicas at 42 Hz and 58 Hz. Downsampling (by a factor of 5) creates aliased frequencies in the [0,15] Hz band. On one hand, the 42 Hz replica creates an aliased version at 12 Hz which will produce zero counts because the ActiLife count bandpass filter (-3dB cutoff [0.3-1.6] Hz [5]) totally attenuates such frequency. On the other hand, the 58 Hz replica creates an aliased version at 2 Hz which will produce non-zero counts. In this scenario, it is thus of the uttermost importance to properly lowpass filter the signal such that 58 Hz replicas do not contribute to the final count output. This procedure is illustrated in Fig. 2 with a boxcar low-pass filter with length m=5 (with a notch at ≈58 Hz, see left column) and with length m=6 (without a notch at ≈58 Hz, see right column). In the former case, 2 Hz frequencies contained in the resampled signal, which represent frequencies within the ActiLife bandwidth, were clearly attenuated compared to the latter case. When using fs that are multiple of fs=30 Hz no replica will be induced in the spectrum as no upsampling is needed.

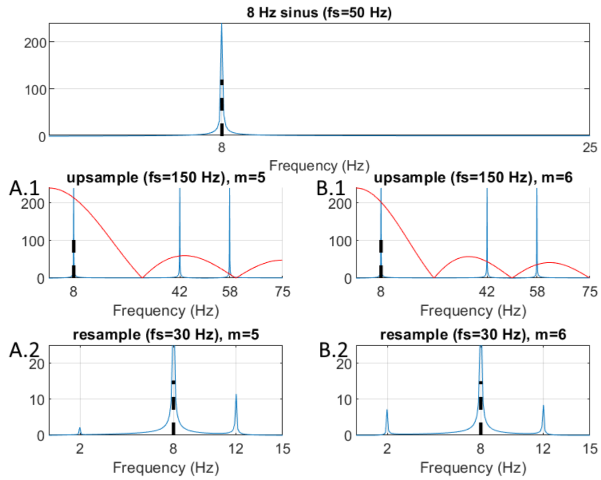

Figure 2. Effect of two different antialiasing filter in resampling processing. Top row: frequency spectrum of a pure 8 Hz sine (only positive frequencies are shown) at fs=50 Hz. Middle row: Frequency spectrum after upsampling 8 Hz sine at fs=150 Hz with a filter of length A.1) 5 or B.1) 6. Red lines represent frequency power attenuation of antialiasing lowpass filter. Bottom row: Frequency spectrum after downsampling the 8 Hz sine (fs=150 Hz) to fs=30 Hz with a filter of length A.2) 5 or B.2) 6. m= filter length.

Fig. 3 illustrates the impact of a simple antialiasing filter with different length on the raw-to-count conversion procedure from raw frequency-sweep sinus (0 to 15 Hz) time series signal of fs=50 Hz and fs=100 Hz. Additional counts, due to 2 Hz aliasing from the resampled signal (see Fig. 2), were found around 10 Hz at m=6 for fs=50 Hz and m=5 with fs=100 Hz. The pattern of these additional counts was similar pattern to those computed by ActiLife software from the same signal (see left column). Whereas no count was found to be computed beyond 5 Hz (see right column) with m=5 for fs=50 Hz and m=7 for 100 Hz, corresponding to the count spectrum computed from ActiLife software from 30 Hz default fs signal (see Fig. 2).

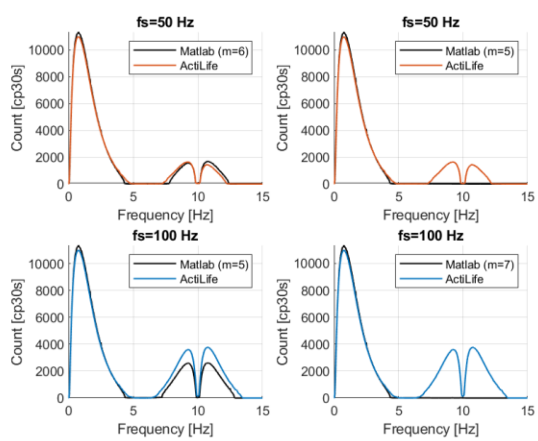

Figure 3. Count computed from frequency-sweep sinus (0 to 15 Hz) time series by ActiLife software after MATLAB procedure antialiasing filter of different length. Orange line corresponds to ActiLife output from fs=50 Hz acceleration signal; Blue line corresponds to ActiLife output from fs=100 Hz acceleration signal; Black lines correspond to count computed from fs=50 and 100 Hz signal resampled to 30 Hz by a MATLAB procedure.

To illustrate the effect of the incorrect resampling on 100 Hz data, we have used a set of accelerometer data collected during a treadmill experiment. Four subjects wearing a hip-Actigraph GT3X+ performed two treadmill-tests with 15 min resting periods between each, cf. Fig. 4. The study protocol was approved by the French Sud-Est 2 Institutional Review Board and all subjects provided a written informed consent. Protocol is detailed in [5]. As expected, the incorrect resampling produced a count overestimation that is visible for some experiments, e.g. experiment #2-#4. The overestimation, that is caused by such aliasing, is in this case 5.2 %. We observe that in some case subjects/walk style the resampling has little effect on count computation. This all depends on the frequency content of the movement under examination.

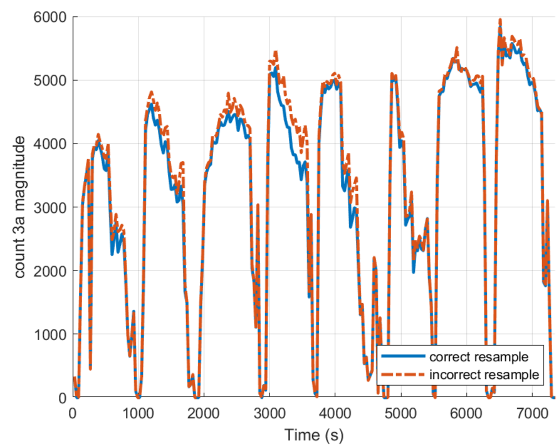

Figure 4. Count computation during treadmill walk/run. The impact of an incorrect resampling causes a count overestimation because of aliasing.

IV. DISCUSSION

In this study, the use of an erroneous antialiasing filter to resample 50 or 100 Hz acceleration signal prior to the ActiLife raw-to-count conversion was shown to induce additional counts computed around 10 Hz whereas ActiLife software initially aimed to totally attenuate signal beyond 5 Hz. We proposed a methodology to adapt antialiasing filter length according to signal fs choice to avoid count overestimation.

Signal downsampling consists in lowpass filtering the signal and then decimate it by a given factor. Correct antialiasing lowpass filter is needed to downsample the signal without inducing replica [8] as illustrated in Fig. 2. Within the frequency spectrum (0-15 Hz) explored in this study, 10 Hz sine acceleration resampling induces an aliased frequency at 0 Hz in absence of filtering from a 50 and 100 Hz sampled signal, while 8 Hz sine acceleration resampling induces an aliased frequency at 2 Hz. Some of the fictitious frequencies induced by an incorrect resampling (e.g. 2 Hz frequency) fall within the count computation ActiLife filter bandwidth (-3dB cutoff [0.3-1.6] Hz [5]) and will produce irrelevant counts. In the default situation (fs=30 Hz), an 8 Hz sine acceleration does not produce any count since it is deemed outside the human movement range. For 50 and 100 Hz fs, a correct resampling should filter out the replicas centered at ±50 Hz before decimation to avoid aliasing produced around 10 Hz. We offer to use a resampling filter of length of 5 for 50 Hz signal and a length of 6 for 100 Hz signal to attenuate the 2 Hz aliased frequency. These results support that the error we observed between ActiLife outputs from different fs is mainly due to the incorrect design of antialiasing filter.

Since the ActiLife software procedure is opaque, its results remain difficult to replicate. Filter and associated parameter presented in this study did not strictly reproduce the patterns of the ActiLife alias around 10 Hz but allowed to identify why it is wrong and to suggest what correction could be applied.

The correction of such an error is of particular interest because unwanted count computation disables comparability between classical study relying on fs=30 Hz and more recent studies relying on fs >30 Hz. Moreover, this error could erroneously induce conversion of count corresponding to non-physiological energy (e. g. vibration, noise) from frequency content beyond the human PA frequency spectrum [9]. The latter observation is particularly important when analyzing data collected during motorized transportation and specific sport activities where accelerometry results exclusively from vibrations. The impact of the overestimation in real life is widely dependent of the activity recorded. Sitting on a chair or lying in bed would be very slightly impacted by the error while activities implying non-physiological vibrations (cycling, boxing, wheelchair, treadmill, motorized transportation) would be clearly impacted. It would be indeed very interesting to undertake further analysis to establish the proportion of overestimation for each activity.

V. Conclusion

This note study is in line with recent discussion strongly recommending using raw data and controlled processing procedure rather than count which depend on related device and software [10, 11]. Nevertheless, to provide comparability and reproducibility across studies still relying on proprietary counts, since our team has already proposed a procedure to replicate the ActiLife counts under MATLAB [5], we recommend the user to resample the data in MATLAB or Python using the appropriate resample function prior to the count computation. The results are supported by numerical simulation and experimental data. This theoretical analysis is validated using an experimental, device-generated data sequence.

Acknowledgment

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