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FILTERING SIGNALS FOR MOVEMENT ANALYSIS IN BIOMECHANICS

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Abstract – Biomechanical analysis of human movement is generally based on various kinds of dynamic measurement, including the measurement of the positions, in a three dimensional space, of reference points fixed on the subject's body and the orientation of body segments. Signal enhancement by proper filtering is often recommended. Often velocity and acceleration signal must be obtained from position-measurement records, which demands special care in numerical processing. Therefore we propose a comparative study of various filtering methods, based both on simulated and experimental signals, in order to develop guidelines for optimum dynamic measurement. Performance of the various methods are examined and compared and indications for their selection and use are provided. Uncertainty evaluation is also addressed. Particular attention is given to filter behaviour in transient conditions.

Keywords: Measurement of human movement, biomechanics, kinematic analysis, signal-filtering in biomechanics

1. INTRODUCTION

The biomechanical study of human movement requires a strict integration between experimental data and models. When dealing with physical parameters that cannot be measured directly, an inverse-dynamics problem has to be solved, which requires the measurement of kinematic quantities, including position, velocity and acceleration of reference points, as well as angular displacement and relative derivatives of body limbs.

State-of-the-art measurement systems for kinematic analysis include video and inertial sensors. In the former case a preliminary calibrated video system is used to measure the position in the two or three dimensional space, according to gesture type and space development, of a set of reference points on the subject where a marker, very clear on the background, is placed. In the latter, an inertial measurement unit, consisting of accelerometers, gyroscopes and magnetometers, is placed of the body segment to measure its orientation in the space. Experimental signals resulting from the measurement are positions in the former and angles in the latter case. In both cases some noise affects the measurements, mainly due to complex electronics and processing of the IMU signals, or to illumination, fast movement and focus in the video case.

On the other hand in a biomechanical analysis positions and angles may be not sufficient, often velocities and accelerations are required to determine internal forces and moments due to the muscle activity. This point is particularly critical since noise heavily affects numerical derivatives [1,13].

In all these issues, filtering is a focal point and several numerical filtering procedures can be considered [4-7]. A common problem of such procedures is their transient behaviour. In fact all of them are based on a processing window and samples in the initial and final part may present an abnormal behaviour, due to the filter. This may not be a problem when dealing with long sequences of a repetitive, sometimes periodic, gesture, but is often a problem when a record of a single gesture is available.

Purpose of this work is to better understand filter performance according to several aspects, with reference to both signal and its derivatives, by using an analytic reference signal and an experimental test case.

The set of filtering methods selected will be firstly introduced considering critically their main features. Then all of them are applied to a reference signal, whose derivatives are calculated analytically and constitute the references, with some random noise added. Performance evaluation will consider both uncertainty on the filtered signal, in terms of signal to noise ratio, and transient performance on signal and its derivatives.

Some practical indications for selecting and defining the parameters of a filter suitable to a particular application will emerge from a critical analysis of performance, and they will be applied to an experimental test case.

2. REFERENCE SIGNALS

The reference signal has been defined considering some typical biomechanical analysis, involving different gestures. Let us then consider hopping and walking analysis.

In the former case, a typical protocol considers the most preferred hopping frequency of 2,2 Hz, which is set by a metronome, to ensure a stable repetition of the gesture [2, 3]. In walking studies generally the step pace is about 2 Hz. Some harmonics has to be considered in the measurement set up, so a frequency band of about 5÷10 Hz, has to be considered [1].

We have generated time histories of the reference signal and its derivatives from the analytical definition with a sampling frequency of 100 Hz, which is compatible with most biomechanical data acquisition systems. Of course it is easily possible to investigate different parameters configuration both for sampling and fundamental frequency.

3. FILTERING METHODS

In this study we have investigated three filtering methods of special interest for biomechanics:

- a moving average filter, MA, with and without a smoothing window,
- a linear zero-phase filter, LF,
- a polynomial filter (according to Savitzky-Golay, SG, [9]).

Let us the briefly introduce and comment upon these three methods.

2.1. Moving average (MA)

Even if its frequency response isn't as performing as for other filter types, due to its intuitive behaviour this filtering method is amply used. It is based on an average window, whose time duration determines its bandwidth, and the consequent number of points to be averaged is determined by the sampling frequency. When short windows are involved together with slow sampling rates, the limitation associated with the minimum number of three points, is critical.

As regards transient behaviour, since the average window of N+1 points, with N even positive integer, is across the central point, the filter enters its regime conditions N/2 samples after start and before the end of the time series. Transient effects are particularly evident when dealing with derivatives. Special smoothing windows might be used to obtain a weighted moving average filter. Of course this procedure will affect both filter bandwidth and transient behaviour. As regards the former, the filter will present a larger bandwidth while considering the latter it will present a smoother transient behaviour. A compromise will be required to maintain the desired noise reduction with a smoother transient management. We are going introduce a Hanning window applied to the points involved in the average, without changing window length.

In the following we will consider a moving average filter with a 3dB bandwidth around 5 Hz, according to the exact number of points included.

2.2. Linear filter (LF)

Butterworth filter is another widely used alternative for filtering biomechanical signals [1]. After a proper design to obtain the desired cut off frequency, the filtering is generally applied two times, in forward and reverse directions, to obtain a zero phase filter.

In the following we will consider a second order 5 Hz cut off Butterworth filter, applied two times to the time series, obtaining a frequency response of 4th order. This is typical for biomechanical application as depicted in [1].

As in the previous case, linear filtering presents a transient behaviour dependent on filter.

2.3. Savitzky – Golay (SG)

Savitzky-Golay is called, after the names of its proposers, a polynomial filter, whose parameters are determined by least square procedure, on a window of points centred on the point of interest [9-12]. The filter set up requires specification of the polynomial order and of the number of points. Cut off frequency depends on both of them and it is rather difficult to determine systematically [10].

The main advantage of this method, from the point of view of biomechanical motion analysis, is that, once polynomial coefficients have been determined in a point, the signal derivative are obtained by analytical derivation, therefore avoiding numerical derivative procedures. This great advantage often overcomes the difficulties in setting up a proper filter for noise reduction, so that SG filter is widely used in biomechanics. In the following we will consider a 4th order SG filter applied on a proper window, determined to obtain a good compromise between selectivity and good derivative performance.

4. TEST PROCEDURE

Once the analytical signal has been generated together with its first and second derivatives, at the required sampling frequency, some noise is added to the original signal, before entering the processing phase.

Numerical derivation of the signal may be obtained in each point as recommended by Winter [1], by an average of the numeric derivative considering previous and successive points. MA and LF filters may be introduced in the procedure at different levels: single pass filtering just after derivation; multiple pass filtering after derivation or filtering after each step, that is to say: signal filtering before and after each derivation process. The third procedure has shown best results in the simulation cases we have analysed, so in the following we will present results from this procedure only.

Such rather complex procedures of numerical differentiation and filtering are not required in the SG case, since it is possible to obtain derivatives directly.

All the software required has been implemented in the MatLab ® environment, where it is possible to easily import biomechanical experimental data.

Table 1 presents filters parameters that we are going to evaluate in the following.

Table 1. Filters parameters

Filter type	Parameters
Moving Average, MA	Window length 0,11 s, corresponding to 11 points @ fs=100Hz - 55 points @fs=500 Hz
Butterworth, LF	Cut off frequency 5 Hz, second order, forward reverse passages
Savitscky-Golay, SG	4th order, window length 0, 23 s : 23 points @ fs=100Hz - 111 points @fs=500 Hz

4.1. Performance indicators

Since we rely on an analytical reference, a performance indicator may be developed starting from the point by point difference between signal, obtained after derivative and filtering procedures, and the corresponding reference signal. This can be considered as an estimation of the measurement error, since the reference simulates the measurand and the signal is the output of the measurement procedure. In order to have an overall parameter, it is possible to consider the overall rms values, and to calculate the Signal to Noise ratio, SNR. Since this is an indicator of the overall performance, the transient effect will be masked by the regime behaviour of the system.

To put in evidence the transient effects we will either evaluate a running SNR and a point by point absolute deviation from the reference, considered as relative to the maximum signal amplitude.

Table 2. Signal to Noise Ratio [dB] for three reference signals with increasing frequency

Ref. frequency – Filtering proc.	2Hz	5Hz	10Hz	2Hz	5Hz	10Hz
Sampling frequency	**100 Hz**			**500Hz**		
Noisy signal	15.7	15.7	15.7	17	17	17
Moving Average, MA	19.9	7.1	-0.7	22.3	7.1	-0.7
MA + Hanning	22,5	13	3,8	30,1	14,7	4,5
Butterworth, LF	24.7	6.7	0.6	28	6,0	0.5
Savitsky-Golay, SG	24.1	22,7	1,9	32,5	27,8	2,4

5. PRELIMINARY RESULTS

Filter effect on the original signal is presented in Figure 1. As expected the performance of the Butterworth filter is evident and demonstrated by SNR in table 2 also.

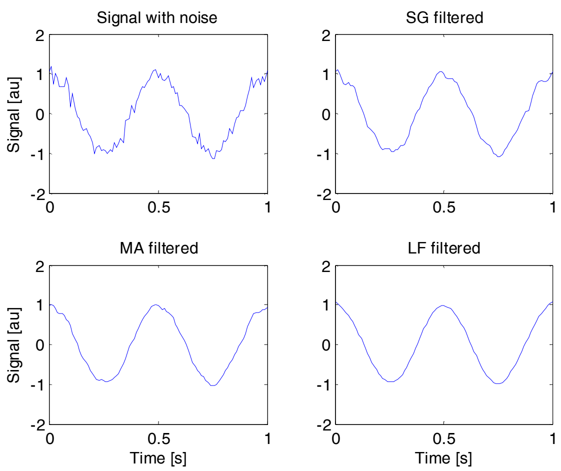

Fig. 1. Reference signal with added Gaussian noise, time signal after SG, MA and Butterworth zero phase filtering.

The first derivative behaviour is much less predictable, as presented in Figure 2 and Table 3.

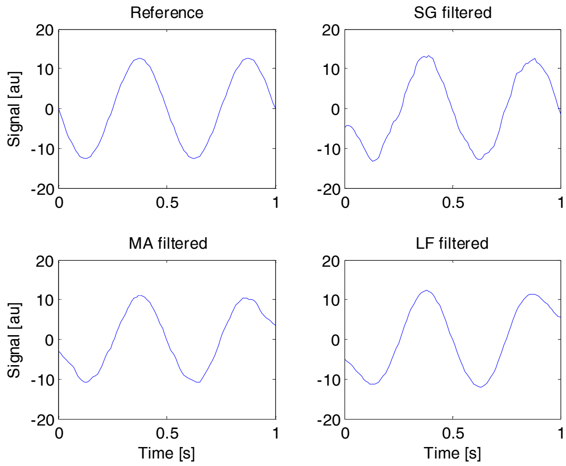

Fig. 2. First derivative: analytical reference, SG filtered, MA filtered and Butterworth zero phase filtered.

In this case the SG filter demonstrates its qualities providing the smallest error in derivation.

Table 3. Signal first derivative Signal to Noise Ratio [dB] for three reference signals with increasing frequency

Ref. frequency – Filtering proc.	2Hz	5Hz	10Hz	2Hz	5Hz	10Hz
Sampling frequency	**100 Hz**			**500Hz**		
Numeric derivative	0,5	8,3	13,5	-11,8	-3,8	2,2
Moving Average, MA	15,2	3,5	0,1	15,5	3,6	0,1
MA + Hanning	18,2	8,1	1,2	22,0	9,4	1,7
Butterworth, LF	16,9	2,9	0,2	19,4	2,7	0,1
Savitsky-Golay, SG	18,9	13,9	-0,4	26,8	14,7	0

The good Savitzky-Golay qualities in derivation are confirmed in the second derivative, even if noise influence is here evident with reduced SNRs (Table 4).

Table 4. Signal second derivative Signal to Noise ratio [dB] for three reference signals with increasing frequency

Ref. frequency – Filtering proc.	2Hz	5Hz	10Hz	2Hz	5Hz	10Hz
Sampling frequency	**100 Hz**			**500Hz**		
Numeric derivative	-16,4	-0,5	10	-42,4	-26,5	-14,5
Moving Average, MA	9,4	1,4	0	9,2	1,5	0
MA + Hanning	10	4,7	0,3	14,1	5,8	0,6
Butterworth, LF	9,6	1	0	11,4	1	0
Savitsky-Golay, SG	7	13,4	0,2	13,4	13,6	0,5

5.1. Transient behaviour

Overall SNR are presented in Tables 2-4 for the signal and its derivatives, for three test signals at 2, 5, and 10Hz. These figures give an idea of the overall performance of the filters, but to emphasize the transient behaviour it is necessary to specifically consider the start and the end of the time series. Running SNR may be useful in this regard as presented in Figure 3. Here the lower SNR near start reveals the effect of the filtering window operating in transient conditions.

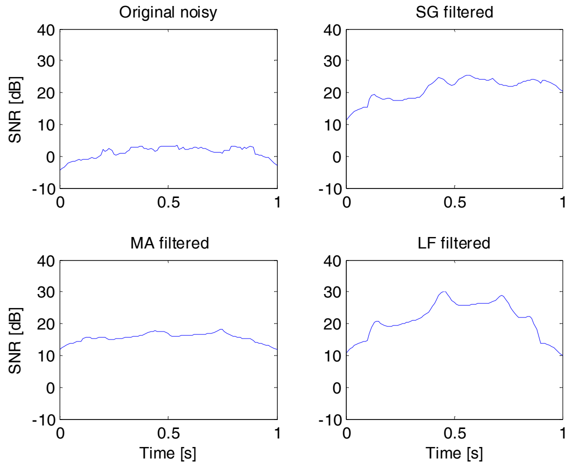

Fig. 3. First derivative running SNR, to emphasize the border effect at time history start and stop.

It is worth noting that common tricks to limit such effects have been implemented, such as moving average variable normalisation while entering and exiting the signal or reflection of a small portion of the signal to obtain a full window when dealing with signal edges. Nevertheless a significant border effect is visible.

Table 5. Relative absolute deviation [%] for signal and its derivatives due to border effects.

Signal Filtering proc.	**2Hz no noise**			**2Hz - SNR 15,7**		
Derivative order	**0**	**1**	**2**	**0**	**1**	**2**
Moving Average, MA	10	31	22	15	27	67
MA + Hanning	4	23	58	11	29	84
Butterworth, LF	5	32	55	9	44	74
Savitscky-Golay, SG	0	4	23	12	38	138

Since a running mean square value depends on window length of course, a more detailed analysis might be based on point by point absolute deviation. Beside that such effect is present in absence of noise also so it is interesting to evaluate it separately considering an ideal signal with infinite SNR. In table 5 we present maximum absolute deviation from the reference relative to the maximum reference amplitude as percentages, for a signal at f=2 Hz, well inside pass-band of all the considered filters, in presence and absence of noise.

Figure 4 presents the time history of the deviation from the reference in the case of no noise, demonstrating clearly the window effect at the borders.

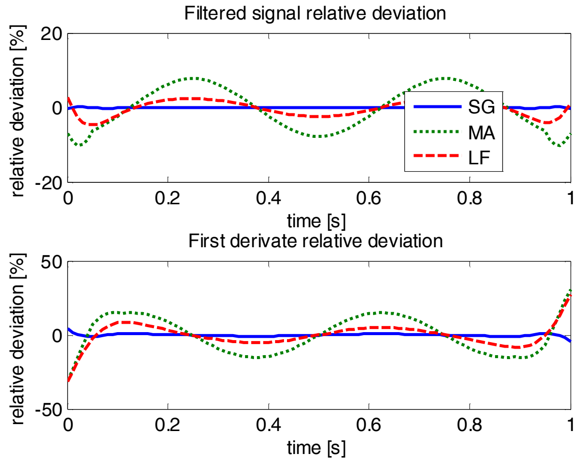

Fig. 4. Deviation from the reference as a function of time without presence of noise. Transient effects are clearly visible.

5.2. Filter selection considerations and test case

It is difficult to give general guidelines for filter selection, we can just sum up the indications we have been able to obtain from previous results.

If the interest is just a SNR improvement both LF and SG perform well, while MA is just a step below, since it presents a larger bandwidth; of course in this specific case a SG filter, with its complex set-up gives no specific advantage except perhaps for the smaller transient deviation.

When one or two derivations are required, generally SG filter seems to be more effective. Yet its setup is critical, since it mainly depends on window length in terms of points and order. As regards the setup some indications follow: the order can be fixed according to expected shape of the signal, and here we fixed it at the fourth order. The window has to be large enough to give a consistent number of points for polynomial fitting. Frequency bandwidth considerations in this case are not straightforward, since window length primarily depends of sampling frequency. As a rule of thumb we have considered a standard MA window which can be settled considering its 3dB attenuation frequency, then we have selected a 2 times longer SG window that has been demonstrated to have a rather good overall average performance. Specific situations such as focus on the high order derivative or low SNR, might find improvement with longer windows.

SG shows a better transient behaviour than LF in pure signal tests, while in presence of noise they present a variable and more or less equivalent behaviour. Errors in estimating signal derivatives near the borders have to be considered since they are not negligible.

5.3. Experimental test case

It is possible to give some more indications after fixing an experimental application. Let us consider for example the measurement of the hip position during hopping. Since hip position is near the full body centre of mass, we are interested in measuring not only position, but velocity and acceleration also. In this case, according to the SNR figures presented previously, the SG filter is the preferred solution and we are going to use the same set up as presented in table 1, third row with sampling at 100Hz.

Figure 5 presents velocity behaviour as computed from experimental data by pure numeric derivation and with the three filters. Raw data refer to measurement of hip position during hopping at about 2,2 Hz.

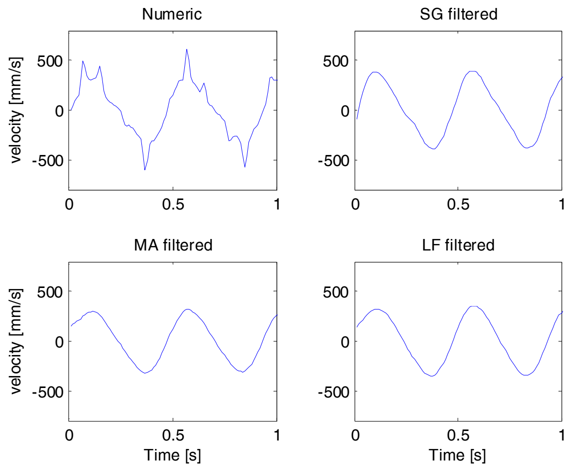

Fig. 5. Hip velocity measurement obtained by filtering hip position measured during hopping at 2,2 Hz.

It is interesting to note that the good SG transient behaviour at the input results in a more appropriate velocity behaviour as compared with MA and LF. Beside that SG maintain a small velocity variation near the zero crossing that with MA and LF is less evident.

Another typical problem in biomechanics is the analysis of a single, non-periodic, event or a specific part of a gesture. In these cases transient effects might be important. As a test case we consider here the foot movement in the anterior posterior direction, during a single contact with ground while hopping at 2,2 Hz, as in the previous case.

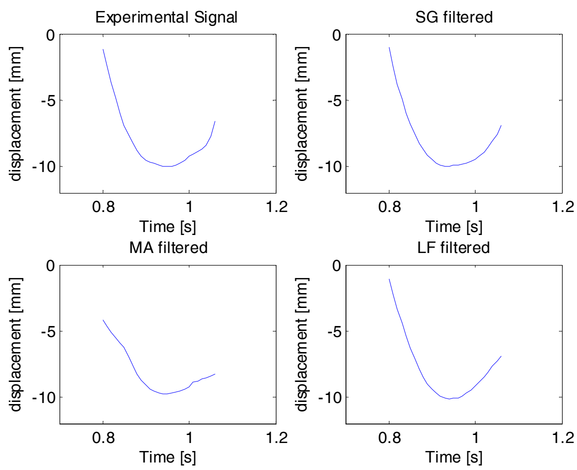

Fig. 6. Foot metatarsus raw and filtered anterior-posterior position measurements during ground contact

Figure 6 shows metatarsus raw and filtered position. We are going to apply here the same set up for the SG filter as for hip velocity, obtaining velocity results as shown in figure 7. In this case border effects might cause significant deviation from expected results, as shown in table 5.

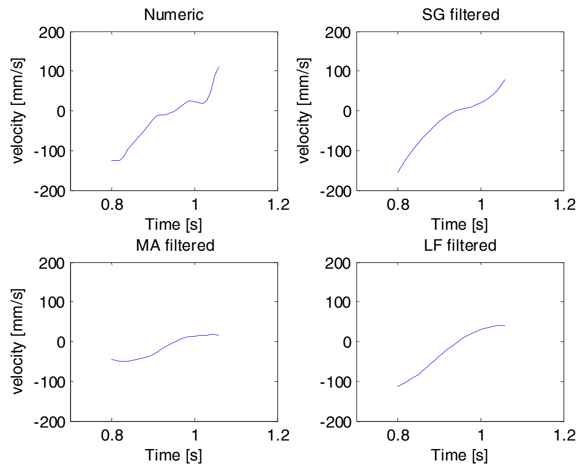

Fig. 7. Foot metatarsus velocity during ground contact, obtained by filtering

A quantitative evaluation requires firstly the evaluation of the SNR for the position signal, obtaining 27dB; then proceeding by simulation, it is possible to evaluate both SG filter transient effect and SNR for signal first derivative, assuming proper frequencies. Some figure are given in Table 6, it is worth noting that SG filter was setup for a 2,2 Hz repetitive signal. Considering intermediate values an overall standard uncertainty for velocity measurement can be estimated around 10%.

Table 6. Uncertainty contributions for velocity measurement in the transient test case.

Signal / Uncertainty contribution	2 Hz SNR 27	3 Hz SNR 27
Maximum relative deviation [%]	±10	±22
Corresponding to a relative standard uncertainty	5,8 %	12,7 %
Expected velocity SNR dB	29	25
Corresponding to a relative noise standard uncertainty	3,5 %	5,6 %

6. CONCLUSIONS

Different filtering procedures have been studied, by applying them to a set of synthetic analytical signals with added Gaussian noise. This has permitted to evaluate filter performance when applied to a known reference signal, considering both the original signal and its first and second derivative. Quantitative performance comparison of the three filters considered has been done through Signal to Noise Ratios evaluated on the overall time history. Transient behaviour has been analysed considering both SNR evaluation on a short time window running on signal time history and point by point deviation. On the basis of simulated results it is possible to appreciate the good performance of the Butterworth filter, but also the validity of Savitzky-Golay filtering above all when the interest is focused on the derivatives. If this is the case, the filter set up has to consider approximately a double length window as compared with moving average, to obtain a good performance in both filtering and derivation.

Different filtering procedures have been investigated. Best performance in the analysed cases was obtained applying filter before and after derivation. Similar performance can be obtained applying the filter one time more than the derivation order.

The paper considered two experimental biomechanical test cases: a periodic and a non-periodic one. In both of them the main focus was the measurement of a velocity from a position signal. We have applied the three filters and Savitzky-Golay confirms its good performance when dealing with derivation. The suggested set up criteria was used in the experimental test case also and the uncertainty was evaluated thanks to the simulation data available.

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