EFFECT OF WINDOW LENGTH WHEN SMOOTHING WITH SINGULAR SPECTRUM ANALYSIS TECHNIQUE IN RUNNING DATA.

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The purpose of this study was to demonstrate the effect of window length on running kinematic data in comparison to data smoothed using a digital Butterworth low pass filter. The raw marker trajectories were smoothed using a digital Butterworth filter with an optimum cutoff frequency and using the SSA technique with window lengths of $L = n/2$, $n/5$, and $n/10$ ($n = 220$). Data smoothing using SSA parameters of $L = n/10$, $r = 2$ produced similar results to the Butterworth low pass filter with an optimal cutoff frequency of 13 Hz. In conclusion, a window length of $L = n/10$ is recommended for running kinematics research, while window lengths of $L = n/2$ should be avoided.

KEY WORDS: smoothing, SSA, running kinematics filter, optimum cutoff frequency.

INTRODUCTION: To eliminate signal noise, various smoothing techniques have been used in biomechanical research. The Butterworth digital filter is one of the most frequently used techniques to eliminate noise. However it has several limitations such as deformation at the both ends of the data row and underestimation of peak values with high frequency signals, like impacts. Time-frequency analysis has previously been used with kinematic impact data (Giakas, Stergioulas, & Vourdas, 2000). Recently the application of a new smoothing technique was introduced (Alonso, Castillo, & Pintado, 2005) which was based on singular spectrum analysis (SSA). This smoothing technique indicated good estimation even if the raw data included a high frequency. The advantages of the SSA technique are simpler algorithms than time-frequency analysis and smaller deformations at the end points than a Butterworth filter. In the SSA algorithm, two parameters; window length (L) and number (r) of principal components should be determined. Selection of these values depends on the type of signal. Particularly the window length L can largely affect the smoothing characteristics. Nevertheless, there are currently no general rules to determine it. Moreover there are very few studies using this smoothing technique within human movement kinematics in sports biomechanics.

The purpose of this study was to demonstrate the effect of window length on running kinematic data smoothing when compared to a Butterworth digital low pass filter.

METHOD: A test data set was derived from a running motion performed by one male subject (age: 23 years, height: 1.72m, body mass: 56.69kg). The subject ran a straight path in a laboratory with 41 retro reflective markers attached on body landmarks. The marker trajectories were obtained using 10 infrared cameras (Vicon MX-13) connected into a three-dimensional motion capture system (Vicon Nexus). The sampling frequency was 250Hz. The subject provided informed consent prior to participation, and the protocol was approved by the Human Subjects Committee at Chukyo University Graduate School of Health and Sport Sciences.

The center of gravity (CG) was calculated using the body segment parameters for Japanese athletes (Ae, Tang & Yokoi, 1992). The 3D reconstructed raw marker trajectory data were smoothed using a fourth order zero-lag digital Butterworth filter with an optimum cutoff frequency (Yu, Gabriel, Noble, & An, 1999) and using the SSA technique. The optimum cutoff frequencies were calculated for each of the 3 components for all markers. The data smoothed with the Butterworth filter was used as the criteria to evaluate the SSA smoothing. Time series raw data is $f_0, f_1, \cdots, f_{n-1}$ with a length of n. In the SSA algorithm, the window length L (L is an integer and $1 < L < n$) is needed to make a Hankel matrix $X = [X_1, X_2, \cdots, X_K]$

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(   ). The length of each column   of the trajectory matrix equals   :
                   ,   . This matrix   is called the trajectory matrix and the size is
       . The trajectory matrix can be expressed as the summation of elementary matrices
                  (is the number of non-zero eigenvalues of the   matrix
and   is the elementary matrix,   ). The norm of the elementary matrix   equals
     (are the non-zero eigenvalues of matrix   in decreasing order). The plot of
               is called the singular spectrum (Figure 1). As in Figure 1, the first   elementary
matrices have a high contribution to the norm with the last representing the signal noise.
Then the matrix   is approximated by   . Finally, the smoothed time series
data are obtained through the reconstruction process (refer to Alonso et al. (2005) for
detailed information).

In this study, the window length   was determined as follows;   ,   and
(,   ,   and   ) with the number   of principal components chosen as   or
        ; as determined from the singular spectrum (Figure 1). Accelerations (markers and CG)
and joint kinematics (joint angle and joint angular velocity of hip) were obtained from right
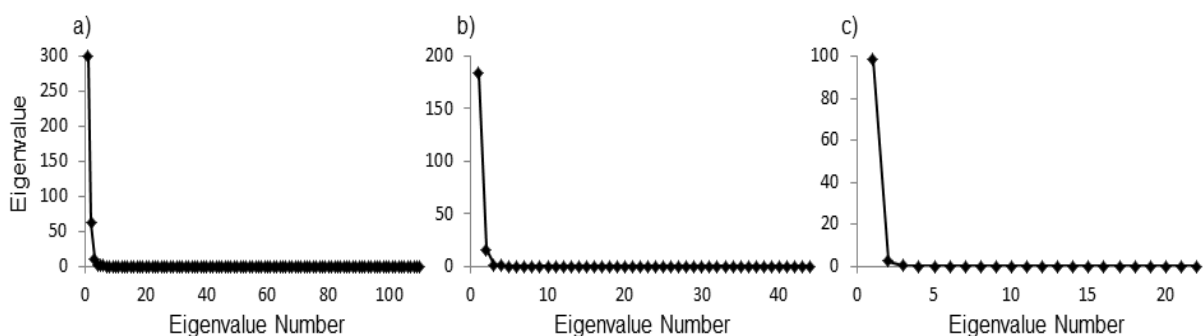foot strike to left foot strike.

Figure 1: Singular spectrum. Window length: *L* = *110* (a), *L* = *44* (b) and *L* = *22* (c). Each *L* corresponds to *n/2*, *n/5* and *n/10* respectively. Time series length: *n* = 220.

RESULTS AND DISCUSSION: The optimum cutoff frequencies for the Butterworth filter were 13.66Hz ±0.028Hz for each data row. The vertical acceleration of the right 5th metatarsal marker had the highest frequency at foot strike. All data smoothed using the SSA technique with   were over-smoothed (Figure 2-a). The Butterworth filter tended to underestimate the peak value, while the SSA technique (,   ) estimated a higher peak value than the Butterworth filter (Figure 2-b). These parameters (,   ) would be useful when the instant of foot strike is to be determined from the marker acceleration curves.

As for the vertical acceleration of CG, data smoothed using the Butterworth filter and SSA technique (,   ) were almost in agreement during the foot contact phase (Figure 3-a). Furthermore, SSA (,   ) demonstrated slightly better agreement with the acceleration due to gravity (   ) than the Butterworth filter during the flight phase (Figure 3-b). However the data smoothed using the SSA (and   ) seemed over-smoothed during both the foot contact and flight phases.

For the hip joint flexion/extension angle and angular velocity, the data smoothed using the Butterworth filter and SSA (,   ) appeared to yield similar results. Therefore the SSA protocol with the parameters   ,   corresponded to a Butterworth filter with a cutoff frequency 13 Hz in this study. However the SSA with   , *r* = *2* showed over-smoothing tendencies. Though the signal characteristic was maintained, the peak values were underestimated by the SSA technique with   , *r* = *2* (Figure 4).

For the data used in this study, the level of smoothing of the SSA with   and the Butterworth filter with an optimum cutoff frequency were almost the same. Within the range of parameters used in this study, the smaller window length brought better smoothing results. Further investigation into the combination of window length and number of principal

components within SSA for other kinematic data with various characteristics from sports biomechanics applications is necessary.
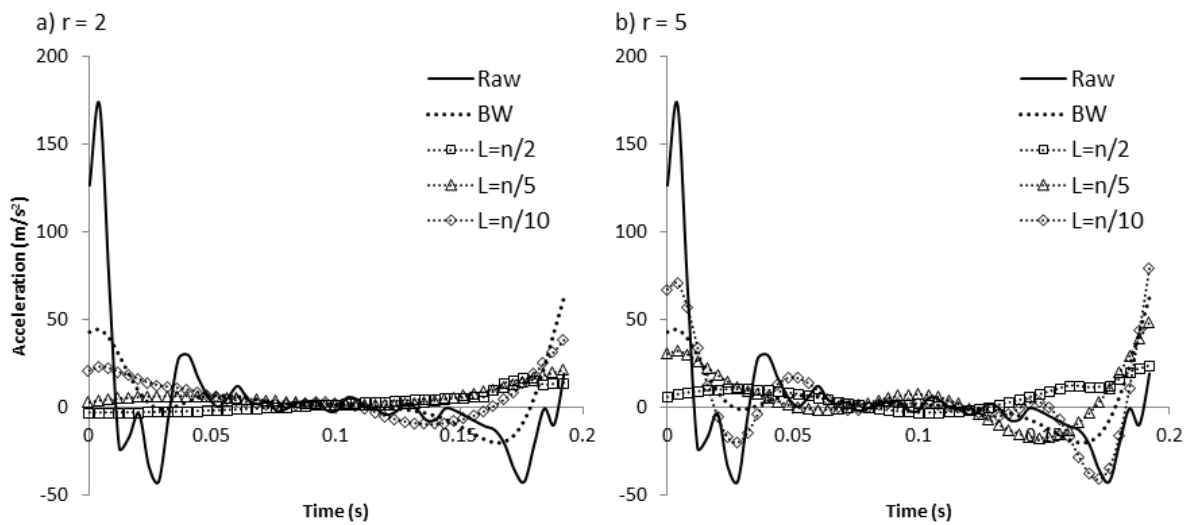

Figure 2: The vertical acceleration of the right 5th metatarsal marker during foot contact phase. The solid and broken lines indicate the raw data and data smoothed with the Butterworth filter, respectively. The square, triangle and diamond marks show smoothed data using the SSA technique with *L = n/2, n/5* and *n/10* respectively. '*n*' is the time series length with a) *r = 2*, b) *r = 5*.
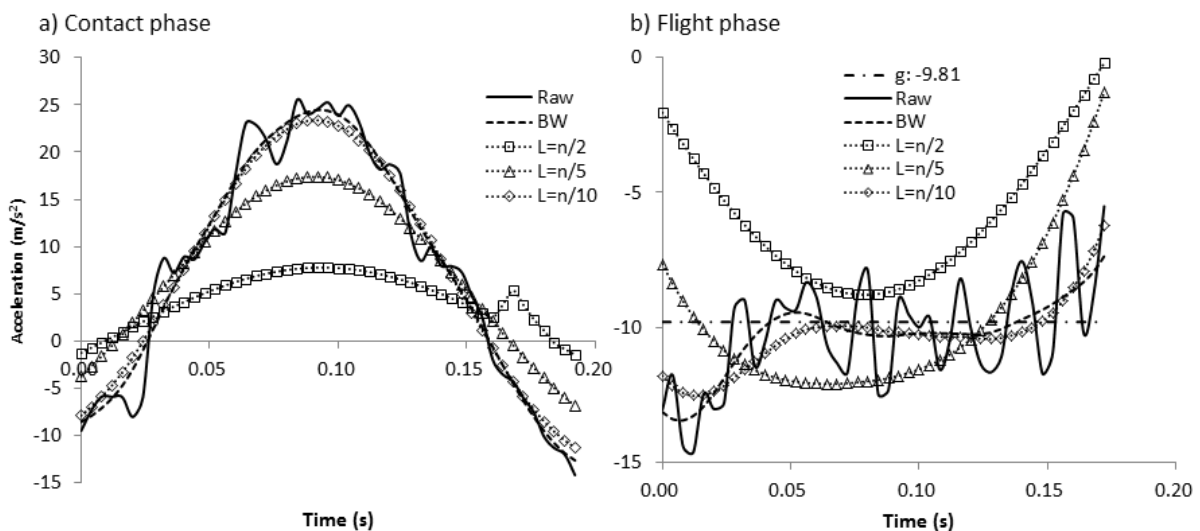

Figure 3: The vertical acceleration of CG. The solid and broken lines indicate the raw data and data smoothed with the Butterworth filter, respectively. The square, triangle and diamond marks show smoothed data using the SSA technique with *L = n/2, n/5* and *n/10* respectively. '*n*' is the time series length with *r = 2*. The dash-dotted line demonstrates the acceleration due to gravity.
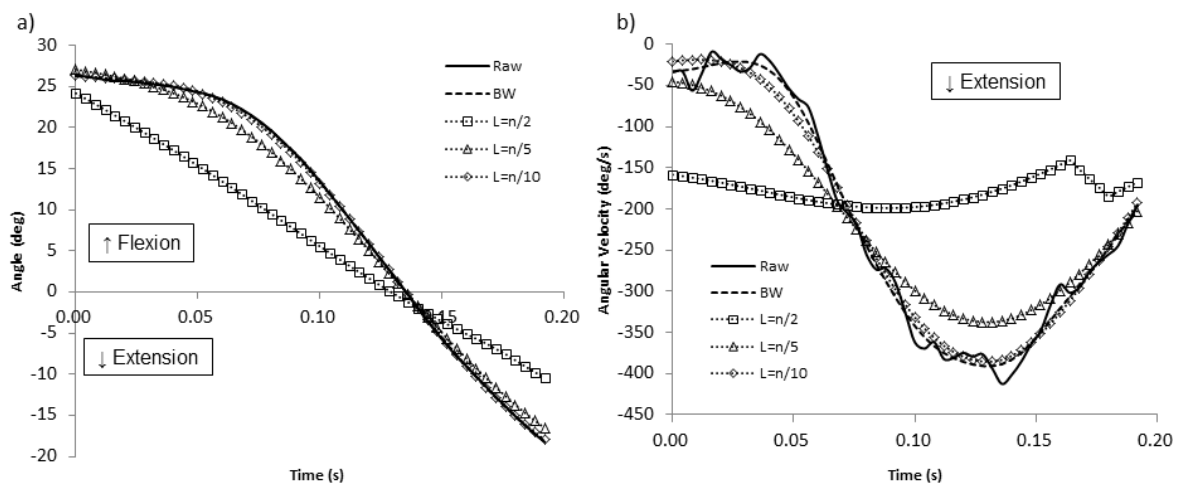
Figure 4: The hip joint kinematic results of a) the joint angle and b) joint angular velocity during foot contact phase. The solid and broken lines indicate the raw data and data smoothed with the Butterworth filter, respectively. The square, triangle and diamond marks show smoothed data using the SSA technique with *L = n/2, n/5* and *n/10* respectively. '*n*' is the time series length and *r = 2*.

CONCLUSION: These results show that the combination of SSA parameters *L = n/10* and *r = 2* was equivalent to using Butterworth digital filter with a cutoff frequency of 13 Hz. A window length *L = n/10* is recommended for running kinematics research, while a window length of *L = n/2* should be avoided. If using marker accelerations, the *r* value should be selected cautiously. The SSA smoothing technique can be applicable to data that includes a high frequency signal and may provide more accurate or realistic smoothed kinematic data.

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