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AN EVALUATION OF FILMING SPEEDS FOR DYNAMIC BIOMECHANICAL MODELING AND RECOMMENDATION FOR OPTIMUM SPEED

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ABSTRACT

This paper recommends the optimum filming speed for developing kinetic biomechanical models for analyzing manual materials handling activities. Using a high speed camera, the lifting activity was filmed at 500 frames per second. Different filming speeds were simulated by skipping one, two or more film frames. The analysis of film data indicated that selection of filming speed based upon cost and accuracy trade-off is a better criterion than any other criteria which have been suggested from time to time.

INTRODUCTION

Cinematography is a popular method for analyzing human body motions for gait, sports, and lifting activities. It involves digitization of film images to determine the displacement profile of the desired body segments. Velocity and acceleration are then determined by taking the first and second derivatives of the displacement curve. One of the major problems in using the cinematographic method is selection of the sampling rate, i.e., the film speed, for recording the body motions. Theoretically, the higher the sampling rate the more frequencies present in the signal can be captured. On the other hand, high filming rates raise the costs of experiment, i.e., film spent, labor for digitizing, and data reduction cost. From the cost viewpoint, therefore, a lower sampling rate is more desirable. Thus, determination of the "right" filming speed is an important step in obtaining an appropriate combination of cost of the experiment and the desired degree of precision.

A wide range of filming speeds has been used in prior studies. El Bassoussi (1974) used a filming speed of 16.7 frames per second while Garg et al. (1982) used a filming speed of 25 frames per second. Neither indicated how the rate was selected. Winter and Wells (1978), based on spectral analysis of data collected on twelve subjects, filmed while walking, recommend using a filming speed of 30 frames per second. This speed was five times (an arbitrary multiplier) the significant frequency content of the signal (approximately 6 Hz). Smith et al. (1982) observed significant differences in forces generated during lifting activities when using various simulated filming speeds (from 102 to 12.7 frames per second). They suggested establishing guidelines for selecting proper filming speed, but made no recommendations.

Different criteria exist for determining the proper filming speeds. The following three criteria have been used from time to time:

(i) Sampling rate should be at least twice the signal frequency (Shannon Sampling theorem),
(ii) Sampling rate should be five times the frequency content of the signal (Winter, 1979; Winter and Wells, 1978),
and (iii) Sampling interval should be such that variance in the second derivatives, due to measurement noise, meet the desired precision (Lanshammer, 1981).

Lanshammer (1981) suggests that if the data are to be differentiated, either once or twice, then the third criterion must be utilized, instead of the first criterion, to improve precision (i.e. to reduce measurement noise level). He developed a formula showing the relationship between sampling rate, noise and variance in the second derivative. Which, if any, of the above criteria is the proper one for kinetic biomechanical analysis is not known. Should the trade-off between the cost and accuracy be the basis for selecting the filming speed? The answers to these questions were sought in this paper. Specifically, the

purpose of this work was to determine the optimum (cost versus accuracy) sampling rate (filming speed) for recording human body motions for biomechanical analysis of manual lifting activities.

METHOD

The experimental procedure involved filming human subjects lifting a 11.36 Kg box from the floor to a table 0.91m high. The motion was filmed at 500 frames per second using a high speed camera (LOCAM II). A white marker was placed around the subject's wrist. The wrist was selected for its highest linear and angular accelerations during the motion studied. A black and white TRI-X reversal film of 400 ASA rating was used. After the film was developed, subject's wrist marker was digitized and the wrist coordinates were fed directly from the digitizer to the disc storage of a MODCOMP Minicomputer. From the film, using instantaneous coordinates of the wrist, a displacement profile of the wrist was prepared. Since the raw displacement data were relatively noisy (due to digitization), they were passed through a Butterworth low-pass digital filter. Thus, noise in the displacement signal was reduced considerably. To determine the cut-off frequency of the filter, a spectral analysis was performed on the raw displacement data. The spectrum of the displacement data, shown in Figure 1, indicates that frequencies above 6 Hz have the characteristics of noise. This noise was eliminated by a Butterworth low-pass digital filter with the cut-off frequency of 6 Hz. The fourth order filter was applied to the data twice, forward and backward. This was done to eliminate phase shifting and to create the effect of an eighth order filter. The velocity and acceleration of the wrist were computed by taking the first and second derivate of the filtered displacement curve. As suggested by Winter (1979), the forward finite difference method was used to determine the derivatives.

To determine the affect of film speed on the accuracy of data analysis, several film speeds were simulated. This was accomplished by skipping one, two, or more frames. Filming speeds of 250, 167, 125, 100, 83, 50, 33, 25 and 16.7 frames per second were thus simulated. The simulated displacement data were filtered and then differentiated twice to obtain acceleration profiles.

RESULTS AND DISCUSSION

To compare the effect of filming speed on acceleration, accelerations calculated from various simulated filming speeds were plotted together. Figures 2, 3, 4 and 5 show a comparison of accelerations at different speeds. The differences in the acceleration peaks can be clearly seen in the figures.

Assuming that the wrist acceleration calculated from data collected by filming at 500 frames per second was error free, relative error of accelerations calculated from data gathered at various simulated filming speeds were computed. Figure 6 shows the plot between relative error (with respect to 500 frames per second) and filming speed. As shown in Figure 6, the relative error decreased with filming speed. The decrease was rapid up to a speed of 125 frames per second. The rate of decrease in relative error was not substantial beyond the filming speed of 125 frames per second. It should be noted here that the total cost (film cost, digitization time, etc.) function is linear and a small gain in accuracy above the filming speed of 125 frames per second is not justified by the increase in filming cost. Therefore, a filming speed of 125 frames per second appears to be optimum (cost vs. accuracy trade off) for filming manual materials handling activities.

The cost and accuracy trade-off criterion has never been used before to determine proper filming speed. All the three criteria that have been used from time to time (see Introduction) yield filming rates substantially different from each other and from the proposed optimum filming speed (125 frames per second). The first two criteria yield filming rates of 12 and 30 frames per second, respectively. These sampling rates should be viewed in the light of Figure 6. Figures 2 and 3 show that acceleration peaks calculated from filming speeds of 12 and 30 frames per second could differ from the reference acceleration peak (from 500 frames per second) by as much as 2 and 0.76m per sec^2, respectively. These differences in acceleration could mean a difference of 8 to 22% in the dynamic force of the box alone.

The third criterion, proposed by Lanshammer (1981), did not fit the actual data pattern. His proposed relationship between variance in the kth derivative, filming speed, and variance of white noise in the signal is given as:

$$\sigma_k^2 \geq \sigma_{k(\text{Minimum})}^2 = \frac{\sigma_f^2 \cdot T \cdot w^{(2k+1)}}{\pi(2k+1)} \qquad (1)$$

where σ_f^2 is variance of white noise in the displacement signal,

σ_k^2 is variance in the kth derivative due to measurement noise,

w is the signal bandwidth in radians/second, and

T is the time interval, in seconds, between two successive frames.

For lifting activities, the signal band width frequency was 6 Hz (=12π rad./sec); value of T was 0.002 sec. (from filming speed of 500 frames/sec.); k was 2 (for acceleration); the variance of white noise in the displacement signal was $(0.18)^2$ cm^2. This gave the minimum value of σ_k^2 equal to 121.92 cm^2. The actual variance in acceleration due to measurement noise was 1.3×10^{10} cm^2.

The difference between the two numbers is extremely large. According to equation (1), as the speed increases, variance in acceleration due to measurement noise decreases. In reality, however, this was not observed. With increase in speed, σ_2^2 also increased. The gain in precision (of acceleration signal) was more than offset by digitization error. For actual data, the value of σ_2^2 decreased with speed - exactly reverse of the theoretical relationship given by equation (1). Lanshammer's criterion, thus, does not lead to selecting proper filming speeds.

From the results of this study, it appears that the proposed cost versus accuracy criterion is very relevant and should be used for determining film speeds. For manual lifting activities, the recommended filming speed (optimum speed), using this criterion, is 125 frames per second.

ACKNOWLEDGMENT

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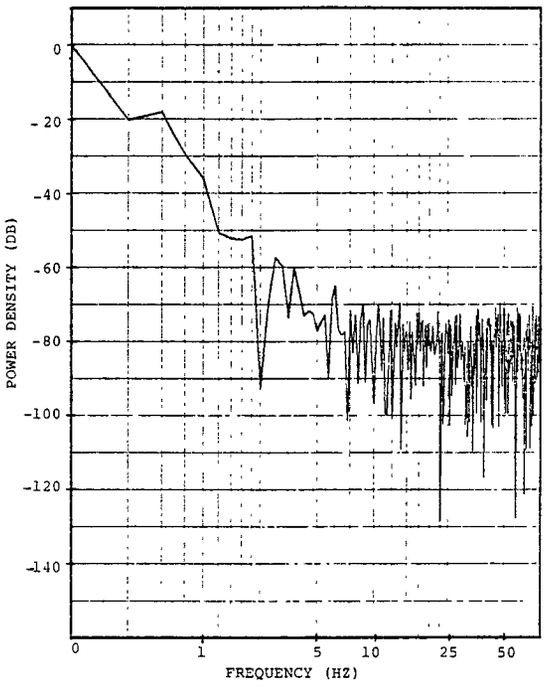
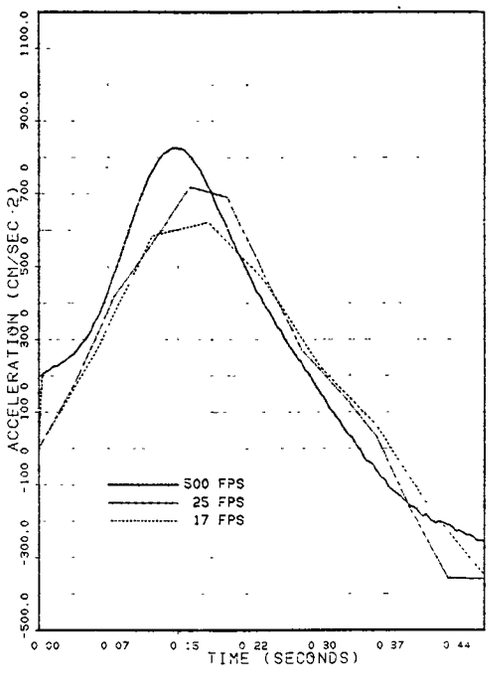


Figure 1



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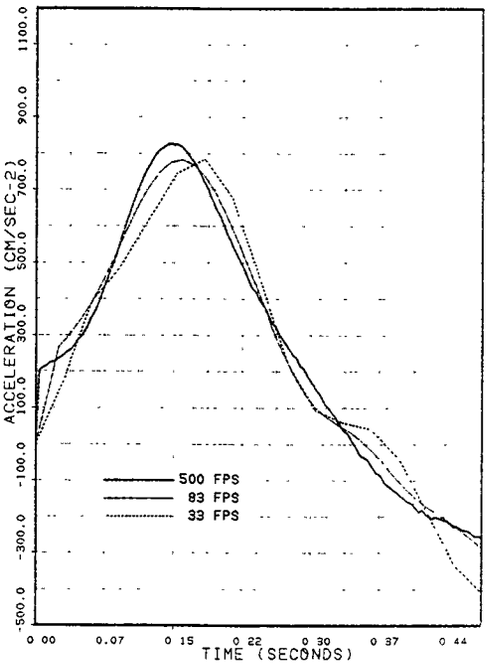

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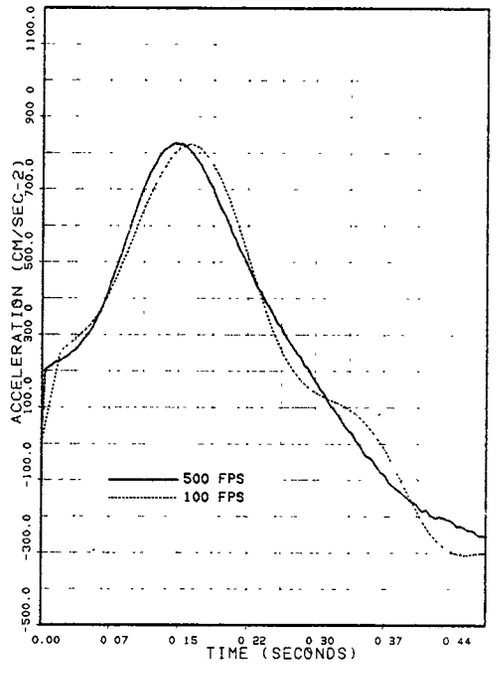

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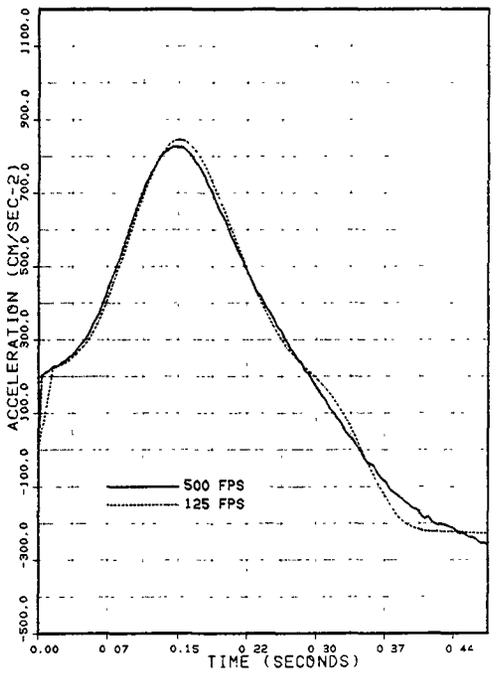

Figure 5

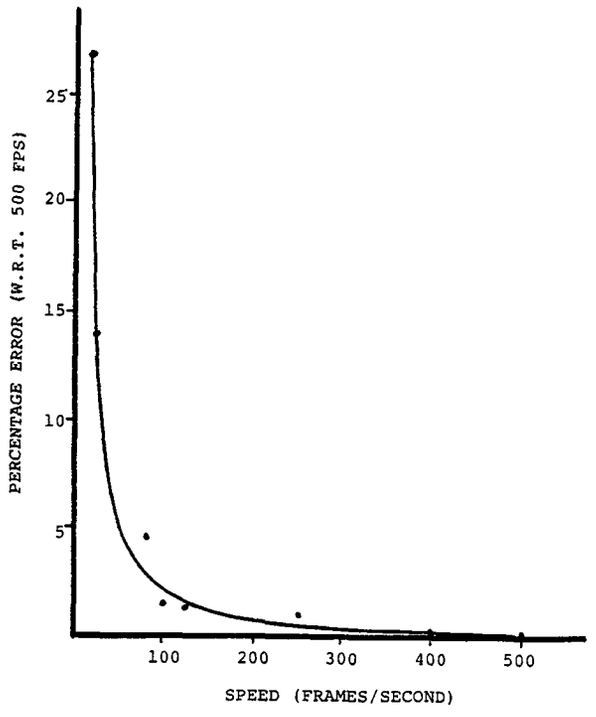

Figure 6