Inverse dynamics is a methodology often utilized in the field of biomechanics [Winter, (1990)]. Instantaneous positions of anatomical landmarks are determined, which are used as kinematic data. Net joint forces, net joint moments and ground reaction forces can be calculated from the kinematic data with an appropriate estimation of body segmental parameter values [de Leva, (1996)]. Typically kinematic data have to be differentiated with respect to time. First and second time derivatives are numerically calculated such as

\[
\frac{dx_n}{dt} = \frac{x_{n+1} - x_n}{\Delta t} = v_n \quad \text{(Eq. 1)}
\]

\[
\frac{d^2 x_n}{dt^2} = \frac{v_{n+1} - v_n}{\Delta t} = a_n \quad \text{(Eq. 2)}
\]

where \(x\) is the position, \(v\) is the velocity, \(a\) is the acceleration, \(n\) is the index to specify the time step and \(\Delta t\) is the sampling time interval. As has been discussed by many researchers in the past [Carslaw, (1930); Cartwright, (1990)], this procedure tends to enhance the magnitude of the noise relative to the signal, which has a detrimental effect on the accuracy of further analyses.

Techniques of digital filtering are utilized to resolve this problem [Gazzani, (1994); Vaughan, (1982); Vint and Hinrichs, (1996a)]. Using this procedure, position data are filtered before their derivatives are calculated in order to reduce the magnitude of the noise relative to the signal, which has a detrimental effect on the accuracy of further analyses.

It was found that the optimal cutoff frequency was underestimated when the experimental noise was imposed on the kinematic data. In other words, the possibility of an information loss was suggested as a result of digital filtering with the cutoff frequency determined through the residual analysis. It was suggested that the optimal cutoff frequency obtained as a result of residual analysis should be compared with the residual - cutoff frequency characteristics obtained through analyzing noise-free kinematics.

**Keywords:** residual analysis, Butterworth digital filter
frequencies (white noise), it is not obvious what cutoff frequency should be utilized. Low-pass filtering is generally utilized in biomechanics, meaning that components of the frequencies lower than the cutoff frequency pass through the filter, whereas components of the frequencies higher than the cutoff frequency are filtered out [Alarcon et al., (2000)]. This implies that when the cutoff frequency is set at a too low value, too much signal is filtered out, whereas when the cutoff frequency is set at a too high value, a large amount of noise passes through the filter.

Therefore, when utilizing the technique of digital filtering, it is important to determine the optimal cutoff frequency that maximizes noise filtering at the same time as minimizing signal filtering [DiGiovine et al., (2000)]. To date, several methodologies to determine the optimal cutoff frequency have been developed [Vint and Hinrichs, (1996a)]. They are based on residual analysis [Winter, (1990)]. The basic principle of this analysis is to evaluate the deviation between the unfiltered data and the filtered data for a variation of cutoff frequencies (from higher frequencies to lower frequencies). The cutoff frequency at which the magnitude of the residual abruptly increases is determined as the optimal cutoff frequency.

Although these methodologies are based on a sound theoretical background [Vaughan, (1982)], there still exists a question, i.e., so far it has not been possible to critically evaluate the outputs of residual analysis. This is probably because noise-free kinematic data of human motions have not been available. Computer simulation can provide an innovative contribution to this issue, as it is possible to generate biomechanically consistent noise-free kinematics using this methodology [Nagano et al., (2000)]. The purpose of this study was to evaluate the appropriateness of residual analysis in determining the optimal cutoff frequency, in reference to noise-free kinematics generated through computer simulation.

2. Methods

As the first step of this study, a 3D musculoskeletal model of the human body was developed using DADS-3D (LMS CADSI, Coralville, Iowa, USA) with the FORTRAN-based USER.FORCE option (Fig. 1.). The musculoskeletal model consisted of nine rigid body segments (head-arms-trunk (HAT), right and left upper legs, right and left lower legs, right and left feet, and right and left toes) connected with frictionless joints. Body segmental parameter values were derived from de Leva (1996). Hip joints were modeled as universal joints that have three degrees of freedom. Knee joints were modeled as hinge joints. Ankle joints were modeled as biaxial joints [Inman, (1976)]. Metatarsophalangeal joints were modeled as hinge joints with a tilted axis [Delp, (1990)]. Thus, the total number of degrees of freedom was 20. Eighty-six Hill-type lower extremity muscles (43 muscles in each leg) were implemented into the model (Fig. 1.). These include all major muscles found in the human leg (all the muscles investigated by Delp (1990)). Muscle parameter values, i.e., the optimal contractile element length, the maximal isometric force of the contractile element, and the pennation angle, were derived from Friederich and Brand (1990). The activation profile for each muscle was specified by three variables, i.e., onset time, offset time and the level of activation [Nagano and Gerritsen, (2001)]. The interaction between the foot segments and the ground was modeled similar to Anderson and Pandy (1999). A full description of this musculoskeletal model can be found elsewhere [Nagano, (2001)].

The musculoskeletal model was used in order to generate two types of jumping motions through
forward dynamic computer simulation: a squat jumping (SQJ) and a counter movement jumping (CMJ) (Fig. 1.). For the SQJ, a simulation was initiated from a squat posture. For the CMJ, a simulation was initiated from an upright posture, with hip, knee, and ankle joints slightly (5 degrees) bent to facilitate the generation of a counter movement.

Muscle activation profiles specified by three parameters for each muscle (onset time, offset time and the level of activation) were modified through an extensive procedure of numerical optimization [Bremermann, (1970)] in which the jumping height was maximized. As bilateral symmetry was assumed, the identical activation signals were sent to contralateral muscles.

Three-dimensional coordinates (X: posteroanterior, Y: caudocranial, Z: mediolateral direction with respect to the upright posture) of six anatomical landmarks, i.e., the acromion, great trochanter, lateral malleolus, lateral epicondyle, heel and fifth metatarsal head, were obtained from the right side of the musculoskeletal model. The sampling was performed at 100 Hz from the start of a simulation to 5 time steps (0.05 s) after the instance of take off. As these coordinates were generated through computer simulation, these values contained only negligible noises.

Thereafter, a Gaussian noise time series (MATLAB, The MathWorks, Inc., Natick, MA, USA) was added to each coordinate to simulate experimental errors (Fig. 3):\[
p(u) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{u^2}{2\sigma^2}} \quad \text{(Eq. 3)}
\]

where \(p\) is the probability function and \(\sigma\) is the standard deviation of variable \(u\). This time series has properties of a white noise, i.e., the power spectral density is distributed evenly through all frequencies, which is assumed to be the nature of random experimental noises involved in typical kinematic analyses.

The standard deviation of the noise was set at 0.01 m, 0.02 m, 0.03 m, 0.04 m and 0.05 m, which cover the range of experimental errors expected when performing a 3D kinematic analysis [Hinrichs and McLean, (1995)]. Residual analysis [Winter, (1990)] was performed on the kinematic data. Bi-directional zero phase-lag Butterwort digital filter was utilized. Optimal cutoff frequency (\(f_{\text{opt}}\)) was determined as the frequency at which an abrupt increase of the magnitude of the residual is observed, when shifting the cutoff frequency from the higher frequency region to the lower frequency region (Fig. 2.). More specifically, \(f_{\text{opt}}\) was determined as the frequency at which the second derivative of the residual with respect to cutoff frequency (\(\Lambda = 0.5 \text{ Hz}\)) became larger.
than a threshold value (0.8 mm/Hz$^2$). This procedure is identical to the one reported by Jackson (1979) and reviewed by Hinrichs (1982).

### 3. Results

Smooth jumping motions were generated both for the SQJ and for the CMJ ([Fig. 1.](#)). Slightly greater jumping height was generated for the CMJ (0.283 m) than for the SQJ (0.281 m).

The overall magnitude of the residual increased as the standard deviation of the Gaussian noise increased ([Fig. 4.](#)). In the relatively higher frequency region (>10 Hz), a larger residual was observed with a larger standard deviation value of the Gaussian noise.

There was a general tendency that as the standard deviation of the Gaussian noise became larger, the optimal cutoff frequency ($f_{\text{opt}}$) became somewhat smaller ([Tab. 1.](#), [Fig. 4.](#)). For example, for the X coordinate of the acromion in the SQJ, the optimal cutoff frequency ranged between 7.0 Hz and 4.5 Hz corresponding to the standard deviation of the Gaussian noise of 0.0 m and 0.05 m., respectively ([Tab. 1.](#)).

4. Discussion

Methodologies of inverse dynamics are often utilized in the field of biomechanics. Kinematic data are numerically differentiated with respect to time in order to calculate kinetic variables, such as forces and moments (one of the most sophisticated examples can be found in Anderson and Pandy (2001a)). As this procedure of numerical differentiation has an effect of enhancing the magnitude of the noise relative to the signal [Carslaw, (1930); Cartwright, (1990)], it is necessary to apply the technique of digital filtering before calculating the time derivatives. Residual analysis [Winter, (1990)] is performed on the kinematic data in order to determine the optimal cutoff frequency of the digital filter. The purpose of this study was to evaluate the appropriateness of the optimal cutoff frequency obtained through the procedure of residual analysis.

A substantial variation was observed for the optimal cutoff frequency value between different coordinates ([Tab. 1.](#)). For example, with the noise level (standard deviation) of 0.03m, the optimal cutoff frequency value ranged between 2.0 Hz - 7.0 Hz for the SQJ and 2.0 Hz - 7.0 Hz for the CMJ. This result suggests that different cutoff frequency values should be applied to individual anatomical landmarks, or even to individual coordinates of a single anatomical landmark [Gazzani, (1994); Vaughan, (1982); Vint and Hinrichs, (1996a).]

Generally, the optimal cutoff frequency value was calculated to be somewhat higher in the SQJ than in the CMJ ([Tab. 1.](#), [Fig. 4.](#)). This may be because of the fact that the duration of the motion was shorter.
for the SQJ than for the CMJ (Fig. 1). The duration of the motion was 0.36 sec and 0.56 sec for the SQJ and CMJ, respectively. A shorter duration of the motion resulted in more abrupt movements of the body segments, which may have resulted in a larger contribution of higher frequency components. The optimal cutoff frequency values obtained in this study are similar to the values utilized in preceding studies: 3.25 - 9.75 Hz, Vint and Hinrichs (1996b); 6 Hz, Nagano et al. (1998); 6 Hz, Voigt et al. (1995); 8 Hz, Kurokawa et al. (2001); 16Hz, Bobbert et al. (1996). This supports that the motions generated through computer simulation in this study have realistic characteristics of human jumping.

There was a tendency that as the noise level (standard deviation) increased, the optimal cutoff frequency shifted toward the lower frequency region (Tab. 1, Fig. 4). For example, for the X coordinate of the acromion in the SQJ, the optimal cutoff frequency ranged between 7.0 Hz and 4.5 Hz, corresponding to the standard deviation of the noise of 0.0 m and 0.05 m, respectively. This result implies that when there exist experimental errors, the optimal cutoff frequency could be underestimated through residual analysis. In other words, by applying the optimal cutoff frequency obtained as a result of residual analysis, there is a possibility that some signals are removed from the kinematics (information loss). To avoid this phenomenon from occurring, it may be recommended to evaluate the residual - cutoff frequency characteristics based on error-free kinematics, as presented in Fig. 4, in this study. Through this procedure, it is possible to evaluate the range of frequencies in which substantial information is contained. This study had strength that it was possible to obtain the error-free kinematics through the use of computer simulation. Therefore it was possible to evaluate the effects of the noise on the determination of the optimal cutoff frequency.

Gaussian noise distribution (Eq. 3) was utilized in order to artificially introduce the noise into the noise-free kinematics in this study (Fig. 3). This distribution has properties of a white noise (power spectral density is distributed evenly through all frequencies). As this is assumed to be the nature of experimental noises involved in kinematic analysis, it can be stated that this methodology simulates experimental settings reasonably well. Bi-directional, zero phase-lag Butterworth digital filter was utilized in this study, as this type of filter is one of the most frequently utilized ones in the field of biomechanics. Application of the main message of this study is not limited to this type of digital filter, but it is also valid for other types of digital filters as well.

Two types of jumping motions, i.e., SQJ and CMJ, were analyzed in this study. Application of the methodology utilized in this study is not limited to these motions. The same procedure can be applied to any other types of motions. For that purpose, noise-free kinematic data that are consistent with the biomechanics of the human musculoskeletal system need to be obtained. Techniques of computer modeling and simulation were utilized in this study in order to generate noise-free jumping kinematics. Other types of human motions have been successfully simulated and published in preceding studies [walking, Anderson and Pandy (2001b); cycling, Neptune and Hull (1998); rowing, Hase and Yamazaki (1997); running, Gerritsen et al. (1995); skiing, Gerritsen et al. (1996)]. Computer simulation of these types of motions can be performed referring to these preceding studies, from which noise-free kinematic data can be obtained.

To summarize the messages of this study, when utilizing the technique of residual analysis, there is a possibility that the optimal cutoff frequency values obtained as the output may not be suitable for the most appropriate filtering. Instead, those results should be compared with the optimal cutoff frequency values determined based on error-free kinematics and adjustments should be made in order to minimize information loss (signal filtering).

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