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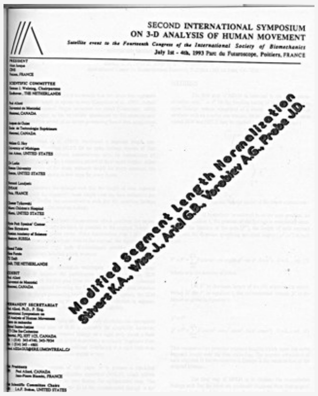
SECOND INTERNATIONAL SYMPOSIUM
ON 3-D ANALYSIS OF HUMAN MOVEMENT

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Article Synopsis

The article discusses the Second International Symposium on 3-D Analysis of Human Movement, held in France in 1993. The focus is on a Modified Segment Length Normalization (MSLN) algorithm developed for kinematic data processing in biomechanics. The MSLN uses the invariance of segment length to reduce measurement error and segment length variability. The algorithm was tested through computer simulation and was found to statistically reduce measurement error. The MSLN method yielded a random error reduction that was 60% better than the Segment Length Normalization (SLN) method. Both SLN and MSLN were found to help a standard smoothing low pass filter to reduce length variability by 1305% relative to the variability obtained by filtering alone. The article concludes that MSLN is a promising kinematic data processing method.

Below find a reprint of the 4 relevant pages of the article "Modified Segment Length Normalization" in "3D conference":

SECOND INTERNATIONAL SYMPOSIUM
ON 3-D ANALYSIS OF HUMAN MOVEMENT

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Modified Segment Length Normalization
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MODIFIED SEGMENT LENGTH NORMALIZATION

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INTRODUCTION

Errors in acquired kinematic data can cause line segments of constant length to appear to vary (Cappozzo et al. 1975). Actual biological segment length variances are small (Obraztsov, 1988) when compared to the variability introduced by the measurement and modeling errors of an image processing based data acquisition system.

Ariel et al. (1993) developed a segment length normalization algorithm (SLN) for an open linkage system of line segments which reduces measurement error by normalizing all segment lengths over a sampling period to their mean lengths. After determination of the mean segment length for every segment, the SLN is implemented in two steps for every frame.

- Reconstruct the linkage such that the length of each segment equals the segment's mean length over the data collection period. Define the reconstruction such that the resulting linkage is close to the original linkage.
- Perform a rigid body displacement which positions the reconstructed linkage as close as possible to the original linkage in the least squares sense. Since construction step 1 places the reconstructed linkage close to the original, the equation for infinitesimal rigid body displacements provides a close approximate solution which is linear.

Through simulation techniques the SLN was demonstrated to improve the performance of a low pass filter. SLN followed with the low pass filter yielded a 7 percent error reduction over that obtained by using the filter alone. For gait data obtained with an image processing based data acquisition system, the SLN followed with filtering yielded a 91 percent reduction in segment length variability over the filtering length variability.

The linearizing small rigid body displacement assumption in the second step of SLN is desirable for simplicity, however, displacing the reconstructed linkage as a rigid body yields a final linkage position which is not necessarily minimally displaced from the original (raw) linkage position. Displacing as a rigid body does not allow the intersegmental angles to vary.

The purpose of this paper is to present a Modified Segment Length Normalization algorithm (MSLN) which allows intersegmental angles to vary during the optimization step. The MSLN will provide a better fit of the reconstructed linkage to the original linkage position.

Through simulation techniques the ability of the MSLN to reduce error and segment length variability will be investigated and compared to SLN.

METHODS

The first step of MSLN is identical to the SLN's reconstruction step. Let $\bar{r}^i$ be the location vector of the i-th joint of an open linkage system comprised of a series of line segments. All symbols with an overbar are vectors. An example linkage system to which SLN and MSLN may be applied is illustrated in Figure 1.

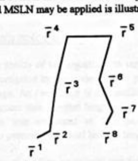

Figure 1. Seven segment linkage model of the lower extremities

$\bar{r}^1$ will henceforth be referred to as the pole position. As given in equation 1, the position of the linkage is completely specified by the location of the pole ($\bar{r}^1$), the length of each segment (l^j), and the direction specifying spherical angles ($\omega^j;\upsilon^j$) at each joint

$$\bar{r}^i = \bar{r}^1 + \sum_{j=1}^{i-1} l^j(\sin\omega^j \cdot \cos\upsilon^j, \sin\omega^j \cdot \sin\upsilon^j, \cos\omega^j) \quad (i = 2,\dots,m) \quad (1)$$

where m is the number of joints.

Let L^j be the mean length of the j-th segment. By substituting L^j for l^j in equation 1, the reconstructed linkage $\bar{p}^i$ is obtained as given in equation 2.

$$\bar{p}^1 = \bar{r}^1$$
$$\bar{p}^i = \bar{r}^1 + \sum_{j=1}^{i-1} L^j(\sin\omega^j \cdot \cos\upsilon^j, \sin\omega^j \cdot \sin\upsilon^j, \cos\omega^j) \quad (i = 2,\dots,m) \quad (2)$$

This reconstruction provides segment lengths which equal the mean segment length over the data collection. The angular orientation of each segment in the reconstructed linkage is the same as that of the original linkage.

The final step of MSLN is to displace the reconstructed linkage such that the joints are minimally displaced from their original positions in the least squares sense. A displaced linkage $\bar{q}^i$ is given in equation 3. To simplify notation $s(\_)$ and $c(\_)$ represent $\sin(\_)$ and $\cos(\_)$ respectively.

$$\bar{q}^1 = \bar{r}^1 + \bar{u}$$
$$\bar{q}^i = \bar{q}^1 + \sum_{j=1}^{i-1} L^j(s(\omega^j+\alpha^j)\cdot c(\upsilon^j+\beta^j), s(\omega^j+\alpha^j)\cdot s(\upsilon^j+\beta^j), c(\omega^j+\alpha^j)) \quad (3)$$
$$(i = 2,\dots,m)$$

where $\bar{u}$ is a translation vector and $(\alpha^j;\beta^j)$ are angular changes.

Since the reconstructed linkage has segments whose angular orientation equals that of the original linkage, assuming that $(\alpha^j;\beta^j)$ are small angles is reasonable. Utilizing the small angle assumption yields equation 4 which is linear in all displacement variables $\bar{u}$, α^j, and β^j.

$$\bar{q}^1 = \bar{r}^1 + \bar{u}$$
$$\bar{q}^i = \bar{q}^1 + \sum_{j=1}^{i-1} L^j(\bar{f}^j + \bar{g}^j\alpha^j + \bar{h}^j\beta^j) \quad (i=2,\dots,m) \quad (4)$$

where

$$\bar{f}^j = (s(\omega^j)c(\upsilon^j), s(\omega^j)s(\upsilon^j), c(\omega^j))$$
$$\bar{g}^j = (c(\omega^j)c(\upsilon^j), c(\omega^j)s(\upsilon^j), -s(\omega^j))$$
$$\bar{h}^j = (-s(\omega^j)s(\upsilon^j), s(\omega^j)c(\upsilon^j), 0.)$$

The requirement that linkage $\bar{q}^i$ be minimally displaced from the original measured linkage position is minimize:

$$\phi(\bar{u},\alpha^j,\beta^j) = \frac{1}{2}\sum_{i=1}^{m}\left|\bar{q}^i - \bar{r}^i\right|^2 \quad (5)$$

Setting the gradient of ϕ equal to zero yields the following $3+2\cdot(m-1)$ normal equations for $\bar{u}$, α^j, and β^j.

$$\bar{e}_s\delta_{sk}\cdot(\sum_{i=1}^{m}\bar{r}^i - m\bar{p}^1 - \sum_{i=1}^{m-1}(m-i)L^i\bar{f}^i) =$$
$$\bar{e}_s\delta_{sk}\cdot[m\bar{u} + \sum_{i=1}^{m-1}(m-i)L^i\alpha^i\bar{g}^i + \sum_{i=1}^{m-1}(m-i)L^i\beta^i\bar{h}^i]$$

$$\bar{g}_t\cdot(\sum_{i=(t+1)}^{m}\bar{r}^i - (m-t)\bar{p}^1 - \sum_{i=(t+1)}^{m}\sum_{j=1}^{i-1}L^j\bar{f}^j) = \quad (6)$$
$$\bar{g}_t\cdot[(m-t)\bar{u} + \sum_{i=(t+1)}^{m}\sum_{j=1}^{i-1}L^j\alpha^j\bar{g}^j + \sum_{i=(t+1)}^{m}\sum_{j=1}^{i-1}L^j\beta^j\bar{h}^j]$$

$$\bar{h}_t\cdot(\sum_{i=(t+1)}^{m}\bar{r}^i - (m-t)\bar{p}^1 - \sum_{i=(t+1)}^{m}\sum_{j=1}^{i-1}L^j\bar{f}^j) =$$
$$\bar{h}_t\cdot[(m-t)\bar{u} + \sum_{i=(t+1)}^{m}\sum_{j=1}^{i-1}L^j\alpha^j\bar{g}^j + \sum_{i=(t+1)}^{m}\sum_{j=1}^{i-1}L^j\beta^j\bar{h}^j]$$

with

$s = 1,2,3$; $k = 1,2,3$ and $t = 1,\dots,m-1$

$\bar{e}_s$ are the unit direction vectors of the reference coordinate system axis. The Einstein summation convention is on s. δ_{sk} is the Kronecker delta. The solution of linear equations 6 is generated numerically using Crout's method with implicit pivoting.

In summary, the mean lengths of every segment are calculated over a sampling period. Equation 2 is used to reconstruct the linkage at every sample (frame). Linear equations 6 are solved to determine the displacement which places the reconstructed linkage a minimum distance from the original linkage. Equation 4 is used with the displacement parameters to obtain the final linkage.

RESULTS AND DISCUSSION

The ability of the algorithm to correct for measurement error was investigated by generating n=360 positions of a four line segment linkage. An i subscript is the position index (i=1,...,360). Each line segment was of equal length. The sum of the lengths of each segment was set equal to 100 so that error is easily represented as percentage of total linkage length.

Error of random magnitude and direction was introduced at each joint. The pseudo random number generator used for this study is that implemented in Borland's C++. Let $\bar{a}_i^j$ be the j-th joint's location in frame i. Thus, if $\bar{r}_i^j$ is the noisy linkage data,

$$\bar{r}_i^j = \bar{a}_i^j + \varepsilon_i^j\bar{\mu}_i^j \quad (7)$$

where

ε_i^j = random error magnitude

$$0 \le \varepsilon_i^j \le \varepsilon_{max}$$

ε_{max} = specified maximum error magnitude

$\bar{\mu}_i^j$ =unit vector in a random direction.

SLN and MSLN are not spectral methods; thus, if analysis requiring velocity or acceleration is required these normalization techniques must be followed with data smoothing.

MSLN, SLN, smoothing, MSLN followed with smoothing, and SLN followed with smoothing were applied to the noisy linkage data. The smoothing technique applied was the familiar three point FIR filter with coefficients of .25, .5, and .25.

As given in equation 8, the ability of each procedure to correct for random error is represented by the root mean squared error over the sampling period.

$$R^c = \sqrt{(\sum_{i=1}^{n}\sum_{j=1}^{5}\left|(\bar{q}_i^{cj} - \bar{a}_i^j)\right|^2)/(n\times 5)} \quad (8)$$

where $\bar{q}_i^{cj}$ is the joint's location obtained by correcting the error data $\bar{r}_i^j$ with method c as listed below.

c	METHOD
1	Raw
2	Smoothed
3	SLN
4	MSLN
5	SLN-Smoothing
6	MSLN-Smoothing

The results are listed in Table 1.

Table 1.

ε max [%]	R^1 [%]	R^2 [%]	R^3 [%]	R^4 [%]	R^5 [%]	R^6 [%]
1.	.71	.47	.64	.61	.43	.41
3.	1.85	1.12	1.68	1.60	1.03	.97
5.	2.98	1.86	2.76	2.59	1.74	1.62
7.	4.16	2.57	3.76	3.60	2.31	2.23
9.	5.34	3.30	4.86	4.63	2.99	2.88
11.	6.49	3.93	6.06	5.73	3.71	3.47
13.	7.73	4.79	7.21	6.84	4.44	4.23
15.	8.81	5.38	8.34	7.91	5.09	4.82

Thus, from Table 1, SLN and MSLN reduces error for all cases. SLN reduced random error on the average by 7.78% with standard deviation of 1.51%. MSLN's average error reduction was 12.5±1.26%.

The smoothing low pass filter yielded an error reduction relative to the random error of 37.9±1.8%. The best error reduction was achieved by following the MSLN with smoothing which had a reduction of 45.5±1.8%. The MSLN followed by smoothing yielded an error reduction which was 5.13±1.2% better than the SLN followed with smoothing approach.

Length variability caused by measurement error can negatively effect kinetic analysis. The problems stem from the prevailing methods of determining inertial properties from segment length. The RMS length variability for all methods is listed in Table 2. V^c is the length variability of method c.

Table 2.

ε max [%]	V^1 [%]	V^2 [%]	V^3 [%]	V^4 [%]	V^5 [%]	V^6 [%]
1.	0.56	0.36	.0000	.0000	0.11	0.11
3.	1.46	0.90	.0000	.0000	0.17	0.16
5.	2.32	1.45	.0000	.0001	0.28	0.26
7.	3.37	2.13	.0000	.0006	0.44	0.42
9.	4.40	2.76	.0001	.0093	0.66	0.62
11.	5.05	3.21	.0001	.0116	1.02	0.96
13.	6.32	4.20	.0005	.0052	1.38	1.31
15.	6.98	4.66	.0006	.0240	1.87	1.91

Thus, SLN and MSLN both reduce length variability to practically zero. On the average, smoothing reduced length variability by onl 36.±1.9% while preceding smoothing with SLN and MSL yielded length variability reductions of 82.4±5.4% and 83.0± 5.7% respectively.

CONCLUSION

A MSLN kinematic data processing technique wa developed for linkages that can be represented as a sequence of lin segments. MSLN uses the invariance of segment length to reduc measurement error and segment length variability.

Using computer simulation, the MSLN was found t statistically reduce measurement error. The MSLN method yielde random error reduction which was 60.% better than the SL method. The best error reduction considered was obtained b following MSLN with smoothing.

Both SLN and MSLN reduced segment variability t practically zero. SLN and MSLN were found to help a standar smoothing low pass filter to reduce length variability by 130% relative to the variability obtained by filtering alone.

Since MSLN was shown to help a traditional smoothing technique to statistically reduce both measurement error and length variability, MSLN is a promising kinematic data processing method.

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