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Comparing derived and acquired acceleration profiles: 3-D optical electronic data analyses

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Advances in technology in the last century have provided the opportunity to observe human behavior in one, two, and three dimensions with higher recording frequencies and greater spatial accuracy. Consequently, detailed analyses of individual trials and composite measures of multiple movement trajectories are possible. However, 3-D data have often been analyzed by performing independent analyses of the limb trajectory along each axis. Essentially, analyses of individual axes are often inappropriate as movement in each axis can contribute to the overall trajectory. Employing such methods can compound error throughout the analysis process. The purpose of this study was to determine appropriate post hoc and real-time 3-D optoelectronic data reduction procedures for manual aiming movements. Rapid goal-directed movements were recorded using an Optotrak and triaxial accelerometer. Data were separately subjected to second order Butterworth filters employing low-cut frequencies of 6–24 Hz in 2 Hz increments. Subsequently, acceleration profiles were derived by double differentiating the individual position profiles and then calculating the resultant acceleration profile. In addition, acceleration profiles were also calculated by finding the resultant position and the total distance traveled each frame prior to double differentiation. Root mean square error between the derived and acquired profiles was employed as our main dependent measure. Trajectories reduced with the total distance procedure produced the lowest root mean square error. The results are important for experimenters analyzing 3-D data post hoc and those implementing real-time manipulations.

Although reaction time, movement time, and terminal accuracy are measures that provide a wealth of information about how humans organize and execute their movements, these performance measures are limited in the extent that they inform researchers about movement control processes. Thus, human movement researchers often use the kinematic properties of the observed trajectories to make inferences about movement planning and execution based on the additional information the kinematics provide in the context of the experimental manipulation. Typical protocols involve examining individual movement trajectories (e.g., Elliott, Hansen, Mendoza, & Tremblay, 2004) as well as variability in performance across multiple trials (e.g., Darling & Cooke, 1987; Khan, Elliott, Coull, Chua, & Lyons, 2002). Motor control processes and how they change with development and practice can be studied over repeated performances and under various sensorimotor conditions by examining the velocity, acceleration, accuracy and precision of the goal-directed movements.

Over the last century, the tools employed to capture and display movement trajectories and their evolution with practice have changed dramatically. The equipment used has included rotating drums (Woodworth, 1899), magnetic trackers (e.g., Desmurget et al., 2005), digitizing tablets (e.g., Khan et al., 2003), and optoelectronic cameras (e.g., Elliott, Binsted, & Heath, 1999). Dependent measures such as velocity, acceleration, and the temporal and spatial location of the peak of those kinematic markers were derived and analyzed once experimenters were capable of tracking the trajectory of the effector.

Although optoelectronic cameras can record movement trajectories with high precision, noise exists in the recorded data. Noise can arise in optoelectronic recordings because of light reflections, and analog to digital conversions. These types of methodological noise should be distinguished from the trial-to-trial neural-motor variability associated with the participant's performance that may be of interest to the experimenter. Noise manifests in the data as values that systematically affect the observed position of the effector at any given time. This noise must be removed from the recorded data to acquire the signal of interest. Since noise is typically characterized by high-

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frequency fluctuations in the signal, recorded data are typically filtered using low-pass filters that remove the high-frequency component of the data while keeping the signal of interest.

A major issue during data reduction associated with a noisy signal is that the noise is inflated through the differentiation of displacement to obtain velocity and the double differentiation to obtain acceleration. This problem is paramount when selecting spatial and temporal criteria for identifying specific kinematic markers. Some criteria are based on the single differentiation and others on the double differentiation. For example, movement initiation and endpoint are often based on the velocity profile and corrective modification are often derived from the acceleration profile. Error that increases during the calculation of the first and second derivatives creates a situation where some of the dependent measures are more reliable than the others. Thus, the compounding error problem makes the selection of a proper filter rate all the more important. A filter rate with a cut-off that is too low can remove the signal of interest and a cut-off that is too high can leave noise in the profile. Currently a cut-off frequency of 10 Hz is recommended for constrained human movement data collected from a potentiometer (Franks, Sanderson, & van Donkelaar, 1990). However, there is presently no standard filter cut-off for unconstrained 3-D optoelectronic data. Although the analysis of the kinematics provides information for a specific trial and captures the variability of motor output over a series of trials, the question remains as to the amount that signal processing noise accounts for in the acquired signal. It is important that the noise associated with measurement error is removed from the signal without removing data that might reflect volitional sensory-based corrections of the movement trajectory or any neural-motor variability of interest.

Over the past few decades, motor control researchers have manipulated the availability of visual information with the intention of examining the deterioration of performance resulting from an absence of this source of sensory information. Specifically, comparing the kinematic data from occluded and nonperturbed trials provides valuable information about the utilization of visual information during goal-directed movement and the structure of the submovements. In general, the interpretation of the kinematics associated with goal-directed action is dependent on the model of limb control the measures were designed to investigate. Experimenters have attempted to quantify visual–motor control by determining the number of discontinuities/corrections in the acceleration profile (Crossman & Goodeve, 1963/1983; Elliott et al., 2004), time after peak velocity (Elliott et al., 1999), index of error correction (Khan, Franks, & Goodman, 1998), variability in the distance traveled at various kinematic markers (Darling & Cooke, 1987; Khan et al., 2002; Messier & Kalaska, 1999), and with correlations between the distance traveled at movement endpoint and earlier kinematic markers or the primary-submovement endpoint (Desmurget et al., 2005; Elliott et al., 1999; Heath, Westwood, & Binsted, 2004; Messier & Kalaska, 1999). Researchers taking a dynamic systems approach have also examined variability in force production and approximate entropy (Sosnoff & Newell, 2005), temporal coupling, average spatial ratios and relative phase variability in the visual control of bimanual circle drawing (Spencer, Ivry, Cattaert, & Semjen, 2005), velocity profile symmetry during reciprocal aiming (Fernandez, Warren, & Bootsma, 2006), and tau-dot and amount of underaiming (Hopkins, Churchill, Vogt, & Rönnqvist, 2004). Each of these dependent measures provides different information about the motor control processes involved in goal-directed movement. For example, an increase in the time after peak velocity (Elliott et al., 1999) and number of discontinuities in the acceleration profile (Crossman & Goodeve, 1963/1983) are related to the presence of visual information. Although results vary, visual information can also lead to decreases in constant and variable error with (e.g., Crossman & Goodeve, 1963/1983) or without a decrease in the number of trajectory corrections (e.g., Elliott et al., 1999).

While many motor control researchers employ kinematic analyses, few use standardized criteria to reduce their data and define trajectory corrections. As such, movement kinematics and discontinuities in the movement trajectory are defined in many different ways. Most definitions include both spatial and temporal criteria. For example, Chua and Elliott (1993) employed a velocity criterion of 30 mm/sec and a temporal criterion of 70 msec to determine the point of movement initiation (see also Meyer et al., 1988; van Donkelaar & Franks, 1991). In this case, the spatial and temporal criteria were selected to correspond to the resolution and collection frequency of the recording device employed to measure the behavior (e.g., optical encoders, potentiometers, digitizing tablets). It is important to note, however, that equipment such as an optoelectronic system is not limited to the collection of data in one or two dimensions and therefore the criteria selected to define the dependent measures becomes arbitrary in a different measurement situation. In this context, the application of criteria derived from the procedures employing other recording tools should be applied with caution, especially when combined with the sensitivity of the calculation of the kinematics to the filtration cut-off. In other words, it is important that the criteria used in our experimental procedures continue to evolve as the technology used to measure behavior progresses.

Recently, advances in movement recording technology have provided the opportunity to collect optoelectronic data and subsequently manipulate the presented experimental stimuli based on the participant's concurrent actions (i.e., real time analysis and task perturbation). For example, Ketelaars, Khan, and Franks (1999) have implemented dual-tasks situations by presenting stimuli at key stages during movement execution (e.g., peak acceleration and peak velocity). The challenge in these techniques is that in order to link experimental manipulations to an ongoing movement, noise must be minimized to reduce the likelihood that events are triggered by random fluctuations in the recorded signal that surpass the established threshold for triggering these events. Therefore, the data must be reduced by another process. A running average of the position profiles is the recommended method of concurrent data reduction (Allard, Stokes, & Blanchi, 1995). However, we are currently unaware of the optimal size of the averaging process that produces a signal with minimal noise and that maintains a short temporal duration so that criteria for manipulations can be established.

In this experiment, participants completed goal-directed movements while under instructions to be as rapid and as accurate as possible. Given the potential for error in the calculation and interpretation of human movement kinematics, the purpose of this study was to determine optimal reduction procedures for 3-D optoelectronic data using post hoc and real-time methods. Accelerometer data were employed as the standard because the noise fluctuations caused by the differentiation procedure is absent in the acquired data. A series of Butterworth filters were employed to determine an appropriate filter rate for post hoc analyses. Two floating average methods were also tested to determine a suitable method for concurrent collection and manipulation.

METHOD

Participants

Six right-handed males from the McMaster University community participated. Ages ranged from 22 to 29 years. Informed consent was obtained from all participants. This study was completed while following the guidelines of the McMaster Research Ethics Board.

Apparatus

An infrared light emitting diode (IRED) was attached onto an accelerometer affixed to a banjo pick and then placed on the index finger of the participant's right hand. An Optotrak 3020 (Northern Digital) measured the location of the IRED for 1 sec at 500 Hz. A triaxial accelerometer (Crossbow Technologies) measured the linear acceleration of the finger for 1 sec at 500 Hz on each of three channels. A pair of liquid crystal goggles (Milgram, 1987) occluded vision for some of the trials. A custom-made software program concurrently triggered the data collection of the Optotrak and accelerometer. The software program that triggered data collection also initiated and terminated the presentation of the experimental stimuli.

The home position was located approximately 20 cm from the torso of the participant. Three yellow target circles 2 cm in diameter could be presented. The home position and the central target were located in the midline of the participant at a distance of 30 cm from each other. The other targets were located to 10 cm to the left and right of the central target and perpendicular to the midline. Therefore the right and left targets were 31.6 cm away from the home position. Participants completed manual aiming movements between the home position and the target with their right index finger. Participants were instructed to make the movements as rapidly and accurately as possible.

Procedure

Trials were completed in two blocks. Participants completed 30 trials under full vision and then 30 trials without visual feedback. Each block of thirty trials contained ten trials to each of the three target locations presented in a random order. Individual trials began with a verbal warning followed by the presentation of a yellow target circle in isolation for 1 sec. Following an additional variable foreperiod of 200–800 msec in increments of 100 msec, an 800-Hz tone was presented as the imperative stimulus. During the no-vision trials, the liquid crystal goggles closed concurrently with the initiation of the imperative stimulus. Termination of data collection was signaled by another 800-Hz tone. Following the second tone, participants were asked to return to the home position and prepare for the next trial.

Data Analyses and Reduction

Post hoc procedures. Optoelectronic position data and the accelerometer data were filtered using a Butterworth filter employing cut-off frequencies of 6–24 Hz in increments of 2 Hz. Axes data from the Optotrak were differentiated in three different ways following the filtering procedures. First, *x*-, *y*-, and *z*-axis data were individually double differentiated and then the resultant acceleration was calculated by finding the square root of the sum of the squared accelerations in each direction. We refer to this procedure as the *resultant method*. Second, the position profile of the IRED was acquired from the square root of the sum of the squared positions in each axis and then that profile was double differentiated to acquire the acceleration profile. In the present article, this was termed the *displacement method*. Lastly, the cumulative distance traveled was calculated for each frame and then double differentiated to obtain the acceleration profile. This final process was termed the *distance method*.

x-, *y*-, and *z*-axis data acquired from the accelerometer were squared, summed and then the square-root was calculated to provide the resultant acceleration. Resultant acceleration data were used as the target values for the calculation of root mean square error (RMSE). RMSE was selected as the dependent measure because it provides an overall measure of the capacity of the derivation methods to attain the acquired acceleration target values. RMSE in this context is a relative term. In other words, the lower the score the better the match between the comparator and the target. Overall, the lowest RMSE is optimal for selecting and analysis process, irrespective of a high or low degree of error. RMSE was calculated as the square root of the sum of the squared deviations of the derived acceleration profile from the acquired acceleration profile divided by the total number of observations. RMSE between the derived and acquired acceleration profiles were calculated separately for the resultant, displacement, and the distance profiles at each of the 10 cut-off frequencies. RMSE values were subjected to a 2 (visual condition: full vision, no vision) × 3 (target: left, center, right) × 11 (filter rate: raw, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24 Hz) × 3 (derivation method: resultant, displacement, distance) repeated measures ANOVA. Significant main effects and interactions involving more than two means were analyzed post hoc with Tukey's HSD with alpha set at .05.

Real-time calculations. Optoelectronic position data were averaged employing three different processes for the purposes of determining the optimal method for real-time calculations. Raw positions were double differentiated without further manipulation, subjected to 3-point and 5-point running averages prior to differentiation. Running averages were acquired by averaging three or five consecutive frames beginning with the first, second and third frame (fourth and fifth) for the first data point and then continuing the process by averaging the second, third and fourth frames for the second data point (fifth and sixth). RMSE between the derived and acquired acceleration profiles was employed as the dependent measure. RMSE values were subjected to a 2 (visual condition: full vision, no vision) × 3 (target: left, center, right) × 3 (filter process: raw, 3-point, 5-point) × 3 (derivation method: resultant, displacement, distance) repeated measures ANOVA. Significant main effects and interactions involving more than two means were analyzed post hoc with Tukey's HSD with alpha set at .05.

RESULTS

Post Hoc Procedures

Analysis of RMSE revealed a main effect of filter rate [$F(10,50) = 11.32, p < .001$]. RMSE associated with the raw profiles was significantly higher than any filtered profile. RMSE was statistically similar following filtration at

8–24 Hz. However, when the profiles were filtered at 6 Hz, RMSE was statistically lower than when the profiles were filtered at rates equal to or above 16 Hz: see Table 1).[1]

A main effect of derivation method [$F(2,10) = 206.27$, $p < .001$] indicated that the RMSE associated with the resultant acceleration (.0371 mm/fr^2) was significantly higher than the position: .0257 mm/fr^2) and distance (.0269 mm/fr^2) derivations. The position and distance derivations were statistically similar. A significant interaction of filter rate and derivation method [$F(20,100) = 7.87$, $p < .001$] indicated that the resultant and position profiles demonstrated higher RMSE than the distance profile without filtering. However, RMSE for the resultant profiles was significantly higher than the other two derivation methods regardless of filter rate. Employing a cut-off of 6 Hz produced RMSE that was significantly lower for the position than the distance derivation. The two methods were statistically similar at each of the other filter rates. While the distance derivation produced similar RMSE regardless of filter rate, RMSE of the position profiles was influenced by the filter rates. Filter rates above 8 Hz were statistically similar. Filter rates between 8 Hz and 18 Hz inclusive were statistically similar. Filter rates of 6–10 Hz produced statistically similar RMSE only for the position derivation (see Table 1).

A significant interaction of visual condition and filter rate [$F(10,50) = 10.33$, $p < .001$] indicated that significantly less RMSE was associated with trials where participants had vision of the movement environment. Although RMSE was significantly different between the visual conditions at each filter rate, similar RMSE was evident for the no-vision condition and the full vision condition at the subsequent higher filter rate (see Table 1).

A significant interaction of target and filter rate [$F(20,100) = 1.86$, $p < .024$] indicated that the RMSE was statistically similar for all targets at each filter rate. However, movements to the left and center targets produced profiles that indicated less RMSE when filtered at 6 Hz than any other filter rate. In contrast, movements to the right target produced profiles that indicated similar RMSE at filter rates of 6–10 Hz (see Table 1).

In addition to the interaction of target and filter, a significant interaction of target and derivation method [$F(4,20) = 9.79$, $p < .001$] indicated that the resultant derivation method produced significantly higher RMSE regardless of target location. Also, the position method produced significantly less RMSE than the distance method only for movements to the right target. The position derivation method was the only method to produce significantly less error for the right target than the left or center targets (see Figure 1).

Most importantly, a significant interaction of target, filter, and derivation method [$F(40,200) = 2.33$, $p < .001$] indicated that the distance method produced significantly lower RMSE when the profiles were not filtered irrespective of target location (see Figure 2). Although the resultant method produced significantly higher RMSE, the RMSE was independent of the movement direction for each filter rate. In contrast, the amount of RMSE calculated following the position method was dependent on the target location regardless of filter rate. Profiles from movement to the three targets produced similar RMSE when filtered at or above 14 Hz when the distance method was employed (see Figure 2).

Real-Time Calculations

Analysis of RMSE revealed main effects of visual condition [$F(1,5) = 34.05$, $p < .002$] and filter process [$F(2,10) = 29.52$, $p < .001$]. Significantly lower error was associated with the full vision condition (.0315 mm/fr^2) than the no-vision condition (.0345 mm/fr^2). Overall, the running averages produced significantly lower error than the raw procedure (.0363 mm/fr^2). However, the 5-point procedure (.0295 mm/fr^2) produced significantly lower error than the 3-point procedure (.0330 mm/fr^2). The analysis also revealed a significant interaction of visual condition and filter process [$F(2,10) = 96.77$, $p < .001$]. Although RMSE was significantly lower when vision was present, RMSE was significantly lower in the 5-point condition regardless of visual condition, while RMSE was statistically similar in the full-vision raw and no-vision 3-point conditions (see Figure 3).

A main effect of derivation method [$F(2,10) = 19.31$, $p < .001$] indicated that the distance derivation method (.0283 mm/fr^2) produced significantly lower error than the position (.0367 mm/fr^2) and resultant procedure (.0339 mm/fr^2). The position and resultant procedures were statistically similar. However, a significant interac-

Table 1
Post Hoc Root Mean Squared Error (in Millimeters per Frame Squared) As a Function of Filter, Derivation Method and Filter, Visual Condition and Filter, and Target Location and Filter

	Filter										
	Raw	6	8	10	12	14	16	18	20	22	24
	.0363	.0262	.0275	.0285	.0291	.0296	.0299	.0302	.0304	.0305	.0307
Derivation Method											
Resultant	.0397	.0324	.0343	.0356	.0365	.0372	.0377	.0382	.0386	.0390	.0393
Position	.0366	.0208	.0225	.0237	.0245	.0250	.0254	.0257	.0259	.0261	.0263
Distance	.0326	.0254	.0257	.0267	.0264	.0265	.0266	.0266	.0266	.0265	.0264
Visual Condition											
Full vision	.0344	.0257	.0270	.0279	.0285	.0290	.0292	.0295	.0296	.0298	.0299
No vision	.0382	.0267	.0280	.0290	.0297	.0302	.0306	.0309	.0311	.0313	.0314
Target Location											
Left	.0368	.0262	.0276	.0287	.0299	.0300	.0304	.0307	.0310	.0312	.0313
Center	.0365	.0256	.0273	.0285	.0292	.0298	.0301	.0304	.0306	.0307	.0308
Right	.0357	.0267	.0276	.0282	.0287	.0290	.0292	.0294	.0296	.0297	.0298

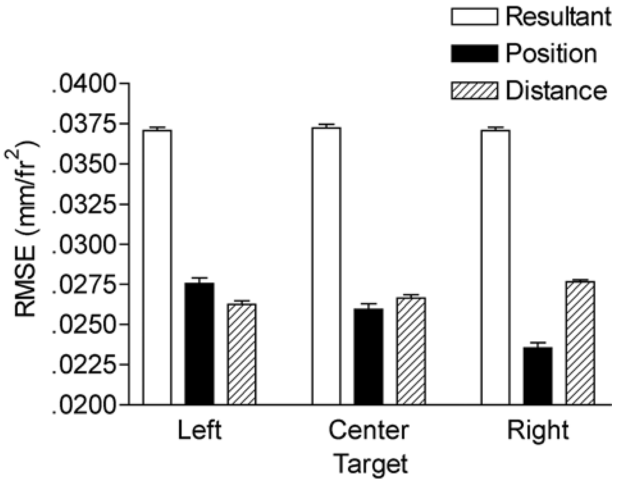

Figure 1. Post hoc root mean squared error as a function of target location (left, center, right) and derivation method (resultant, position, distance).

tion of target and derivation method [$F(4,20) = 7.88$, $p < .001$] indicated that the resultant and position procedures produced similar error for movements executed to the left target only. The resultant procedure produced similar RMSE values regardless of target location and the position procedure produced significantly lower error for movements executed to the right target than the left target. Most importantly, the distance procedure produced statistically similar error regardless of target location and produced significantly lower error in each of the target conditions compared to the other derivation methods (see Table 2).

The analysis also revealed a significant interaction of filter process and derivation method [$F(4,20) = 11.58$, $p < .001$] (see Table 2). RMSE was significantly reduced for all derivation methods following both the 3-point and 5-point procedures. However, the distance procedure produced significantly lower RMSE regardless of the filter procedure. In fact, the error from the positional procedure was only significantly lower than the raw distance procedure following the 5-point procedure. In addition, RSME in the resultant procedure filtered by the 5-point average was only statistically similar to the RMSE in the raw distance procedure (see Table 2).

Timing Variables

Following the analysis of the acceleration profiles data were filtered at 8 Hz and then subjected to a reduction program employing the cumulative distance profile to determine reaction time and movement time for each trial. Reaction time was determined as the time between the initiation of the Optotrak recording and the first frame that the velocity of the finger increased above 10 mm/sec and remained above that criterion for 20 msec consecutively. Movement time was determined as the time between the reaction time and the first frame that decreased below 100 mm/sec for 20 msec consecutively. Data were analyzed by employing a 2 (visual condition: full-vision, no-vision) × 3 (target: left, center, right) repeated measures ANOVA. The separate analyses revealed a main effect of visual condition [$F(1,5) = 20.22$, $p < .007$] for the reaction time analyses and a main effect of target [$F(2,10) = 4.21$, $p < .047$] for the movement time analyses. Participants initiated their movements in a shorter amount of time when visual information was removed at the movement imperative (196 msec) than when vision remained throughout the trial (235 msec). Participants also completed their movements to the right target (404 msec) faster than to the left target (421 msec). Movements to the center target were of intermediate length (412 msec).

DISCUSSION

The purpose of this paper was to determine optimal post hoc and real-time reduction procedures for 3-D optoelectronic data collection. For both procedures the results indicate that movement kinematics should be calculated based on the cumulative distance profile. Double differentiation of the cumulative distance profile produced acceleration profiles with the lowest observed error without significant differences between target conditions. Most strikingly, the resultant profile produced a large amount of error. Recall that the resultant profile was calculated from differentiating the signal in each axis prior to calculating the resultant whereas in the displacement and distance profiles, the resultant was calculated prior to differentiating the signal. Since differentiation procedures increase fluctuations due to noise, error between the acquired and derived resultant acceleration profile can occur because the profile can be

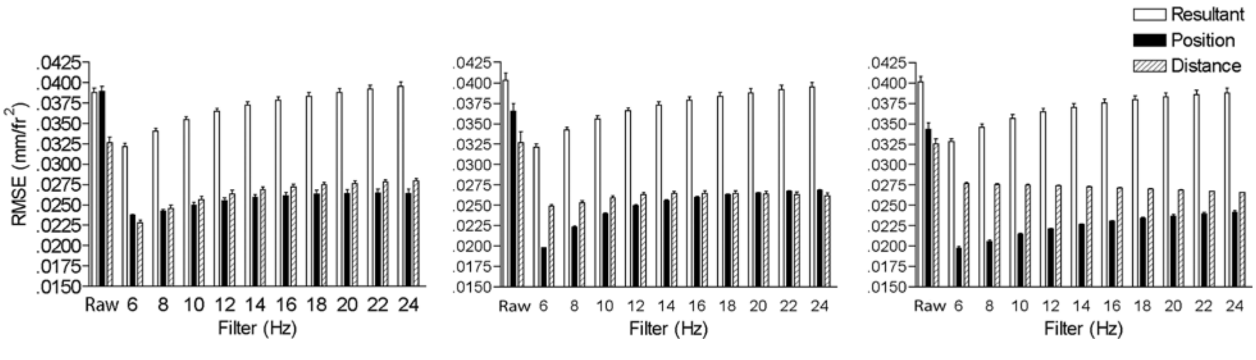

Figure 2. Post hoc root mean squared error as a function of target location (left, center, right), derivation method (resultant, position, distance), and filter (raw, 6–24 Hz).

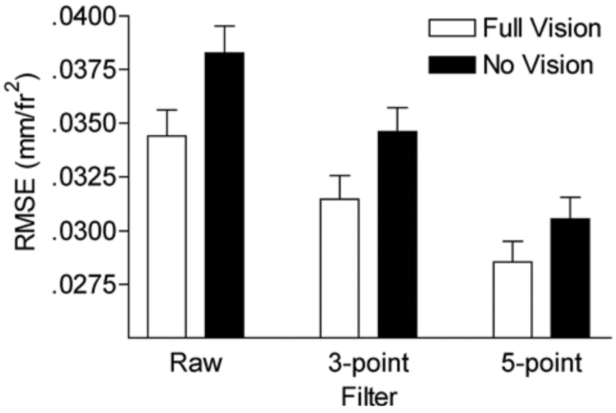

Figure 3. Real-time root mean squared error as a function of visual condition (full vision, no vision) and filter (raw, 6–24 Hz).

over and underestimated when there is large movement in one dimension with or without small movement in another dimension. In other words, the resultant acceleration profile is misrepresented because the combined distance traveled in each individual axis is not equivalent and often larger than the actual distance traveled by the limb. Therefore calculation error remains when determining each individual velocity and acceleration and then determining the resultant acceleration magnitude. These facts also highlight the need to ensure that the frame of reference and the coordinate system is correctly defined.

Fundamentally, the displacement profile should not be used because the same magnitude can be acquired from a series of 3-D locations the same magnitude from the origin of the frame of reference. In other words participants can travel a large total distance and still end up at the same distance from the origin. Although the displacement of a movement can be less than the distance traveled, it must be equal to or less than the distance traveled. Consequently, the velocity and acceleration of the movement trajectory calculated based on the displacement profile is under and over represented relative to the actual event.

Aside from the methodological rationale behind the employment of the cumulative distance profile, a theoretical reason to employ the cumulative profile is that it simplifies the estimation of energy consumption throughout the experiment and can help to index overall movement economy (Elliott et al., 2004; Sparrow & Newell, 1998). Measures such as these will greatly contribute to the measurement of human movement because evidence exists that indicates that individuals decrease their total energy expenditure by decreasing the distance traveled and movement time each trial (Elliott et al., 2004).

Table 2
Real-Time Root Mean Square Error (RMSE, in Millimeters per Frame Squared), With Standard Errors of the Means, As a Function of Derivation Method and Target Location, and Derivation Method and Filter

	Derivation Method					
	Resultant		Position		Distance	
	RMSE	*SE*	RMSE	*SE*	RMSE	*SE*
Target Location						
Left	.0360	.0012	.0359	.0011	.0281	.0015
Center	.0373	.0015	.0339	.0011	.0282	.0015
Right	.0368	.0014	.0318	.0014	.0286	.0015
Filter						
Raw	.0399	.0015	.0366	.0013	.0326	.0016
3-point	.0366	.0013	.0340	.0012	.0284	.0014
5-point	.0337	.0010	.0310	.0009	.0239	.0010

Results form the post hoc analysis indicated that no differences were found between target conditions for the distance profile filtered at or above 14 Hz. However, error associated with the right target remained statistically similar regardless of the cut-off frequency and error associated with the left and center targets was statistically similar across cut-off frequency. In addition, irrespective of target location, there were no differences between filtration at 8 Hz and 14 Hz. Thus, a Butterworth filter with a low-cut frequency of 8 Hz is probably appropriate for post hoc analyses of temporally unconstrained 3-D optoelectronic data unless of course the meaningful higher frequency discontinuities are anticipated in individual acceleration profiles (i.e., between 8 and 14 Hz). Acceleration profiles were also compared following application of 3 and 5-point floating averages because post hoc reduction procedures cannot be applied during real-time data collection. Data reduced with the 5-point average of the total distance traveled produced the lowest RMSE while maintaining the short temporal delay for real-time manipulations.

Trade-offs exist when selecting filter cut-off frequencies. The challenge behind selecting an optimal cut-off frequency is to ensure that noise associated with measurement error is removed without removing evidence of volitional control or neural-motor variability of interest. In other words, the cut-off frequency employed affects the magnitude of the dependent measures (Franks et al., 1990). More discrete events such as reaccelerations and zero crossings in the velocity and acceleration profile remain in the observed signal when higher cut-off frequencies are employed. As such, more kinematic markers are identified for analysis because the increased magnitudes of the events within the velocity and acceleration profiles reach the lower limits of the spatial and temporal criteria used to define the dependent measures. In this context and given the results of the present experiment, when attempting to observe discrete changes in the trajectory a cut-off frequency of 14 Hz is optimal because the events of interest are more evident. In contrast, a cut-off frequency of 8 Hz is optimal when the continuous behavior over time is of primary interest because the overall behavior is maintained without an exaggeration or influence of kinematic events in the individual movement profiles. Overall, the selection of a cut-off frequency should be driven by the dependent measures of interest and how they impact the model of sensorimotor control under investigation.

The present article examined the use of 3-D data reduction procedures on a 3-D data set. Previously, researchers have only examined these reduction techniques in a constrained one-dimensional situation (Franks et al., 1990). Employing tools such as optoelectronic systems allows experimenters to examine the temporal and spatial structure of behavior on limited and extended time scales to evaluate motor control processes, sensory processing times, and motor learning. Proper reduction techniques ensure that experimenters examine trajectories and overall behavior rather than discontinuities that could potentially be considered artifacts in the individual trials. In this context, the results of this experiment are important for individuals reducing optoelectronic data and experimental manipulations based on the concurrently observed behavior.

AUTHOR NOTE

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NOTE

1. Data are presented in mm/fr^2. Multiply the values by 250 for a conversion to m/sec^2 for data collected at 500 Hz.

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