Considerations Related to Modeling the Maximum Reach Envelope (MRE) as a Sphere

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Abstract. The purpose of this study is to examine the effects of the number of data points on modeling the MRE using a sphere. The fitting routine was performed on data sets containing 1800, 600, 300, 100, 50, 20, and just 10 data points for each subject. It was demonstrated that the model generated using as few as 10 points was not significantly different from a model generated when using all 1800 points. The model accurately represented the reach envelopes, with an average overall error of 2%. All the models closely fit the MRE near the central region (± 5 mm) of the reach envelope but at the extremes of the envelope the error in the predicted MRE increased to 40 mm. These findings have implications for the reach surface modeling techniques and the types of reach measurement systems used in the future.

INTRODUCTION

There are numerous safety and performance factors related to the location of controls, handles and materials beyond the maximum reach envelope (MRE) of the operator. For example, in the case of an emergency if a stop button or handle is outside the MRE of its operator when an accident occurs, vital time is wasted and dire human or system failures can occur. Research has clearly shown that requiring a worker to work beyond the MRE for extended periods of time increases the risk of injury. For these and other reasons, the emphasis has been to design workstations such that all tasks are within the maximum reach envelope of 95% of the workers in that population. Typically the reach envelopes are predicted based on the functional reach measurements of a sample of the population and when necessary specific other criteria such as chair designs are included in the measurement process.

Previous investigators have used a variety of methods to record and model the MRE. Farley (1955), conceptualized the area in which people work and defined both a normal and maximum working area for the average operator. The model he devised to compute maximum reach involved using the shoulder as the fixed pivot point of a sweeping extended arm that produced a perfect sphere. The radius of this sphere was equivalent to arm length. However, little attention was paid to the errors associated with this modeling method. Sengupta and Das (2000) applied the concept of a sphere and a non-linear optimization routine on empirically measured reach points to describe the 5^{th}, 50^{th} and 95^{th} percentile MRE for males and females in a seated and standing posture. They reported that their data collection methodology was quick and easy to use with overall accuracy of 25 mm or 4% of the radial length.

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The main objectives of this investigation were to: (a) model MRE using a non-linear least squares routine that fits a sphere to a MRE, (b) determine the error associated with different regions of the spherical model; and, (c) test the hypothesis that there are differences in the various parameters of the modeled spheres (Cartesian coordinates of the sphere origin, radius, and least squares error) based upon the number of sampling points used to obtain the model.

METHODS

Twenty male university students, between 18 and 22 years of age with a height range of 158.3 to 191.5 cm, volunteered for the experiment and completed a document of Informed Consent. Subjects were selected based on a stratified sampling method of convenience. Subjects were placed in one of seven strata based on their height. The number of subjects allocated in each stratum represented the normal height distribution of North American males.

Data collection: The Qualysis Pro-Reflex motion capture system was used to collect 3D coordinate data on each subject. Subjects were seated in an adjustable chair so that their included hip, knee and ankle joints were at approximately 90°. Reflective markers were placed on the acromion, xiphoid process and on the top center of the chair back. A fourth marker was positioned on the top of a cylindrical piece of wood doweling, which had a length of 10 cm and a circumference of 1 cm. The wood doweling was held in the subject's right hand using a pinch grip. Subjects were instructed to keep their upper body motionless and in contact with the chair back. Their elbow was to be extended and their wrist in a neutral position at all times.

Each subject performed three, thirty-second trials of the MRE motion. Data were collected at a frequency of 20 Hz and five cameras were positioned around the subject to record the motion. Three trials of 600 data points were collected of each subjects' MRE.

Spherical model: A non-linear optimization routine was used to determine the sphere of best fit for the maximum reach data for each subject. The model uses equation 1 as shown below and determines the combination of X_c, Y_c, Z_c and R that minimizes the Error term. The variables in this equation represent, R is the radius of the sphere, X_c, Y_c, and Z_c are the coordinates of the origin of the sphere and X_i, Y_i, and Z_i are the i^{th} coordinate values of a subject's MRE.

$$\text{Error} = \sqrt{[(X_i - X_c)^2 + (Y_i - Y_c)^2 + (Z_i - Z_c)^2]} - R, \qquad (1)$$

All X, Y, and Z coordinates are given relative to the acromion marker as the origin (0,0,0).

Reduction of maximum reach data: The reach data from each of the three trials were combined into one large file containing 1800 points. From this master file, eight additional subsets were systematically generated. The first three subsets contained 600 points and were the three initial trials. The next five subsets were generated from the master file of 1800 points. They consisted of 300, 100, 50, 20 and 10 points, respectively. These data sets were constructed by selecting every 6^{th}, 18^{th}, 36^{th}, 90^{th}, and 180^{th} point from the master file of 1800. All modeling and data reduction was completed using MATLAB 5.0.

Model comparisons: For each of the nine model runs the origin of the sphere, the radius and the overall error was determined and used as the dependent measures. Separate two-way analyses of variance (ANOVAs) were performed on each of the five modeled sphere parameters; X_c, Y_c, Z_c, R and error. The two factors used were subjects and groups, where each group contained a different number of points. Further hypothesis tests, to detect differences between the master file and other subsets alone, were conducted when the ANOVA found significant differences. These hypothesis tests included a two-sample T-test and a Wilcoxon Rank Sum test.

RESULTS

Presented in Table 1 is the output of the MRE model for each subject using all 1800 data points. The mean error for all subjects was found between one and two percent of the radii length, except for subject 7 (11%). Subject 7 seemed to be anomaly throughout the investigation and for this reason was left out of any average calculations.

Table 1: Model output for the 5 parameters for all subjects (all dimensions are in mm, * subject 7 removed from MEAN and SD calculations).

Subject	X_c	Y_c	Z_c	Radius	Mean Error	% of Radius
1	-20	-38	-35	620	10	2%
2	-21	25	-41	662	10	2%
3	-46	-3	-101	718	18	2%
4	-44	-24	-50	680	12	2%
5	0	-9	-109	719	10	1%
6	-50	14	-17	665	9	1%
7	35	50	108	572	63	11%
8	10	-15	-44	686	11	2%
9	-25	-24	-62	705	14	2%
10	-28	-22	-41	742	10	1%
11	19	-42	-70	705	12	2%
12	1	22	-75	717	8	1%
13	-31	3	-27	738	16	2%
14	66	-60	-5	742	10	1%
15	42	-86	-25	753	11	1%
16	-13	-28	-82	778	11	1%
17	10	-24	-62	723	9	1%
18	17	-11	-49	764	12	2%
19	2	7	-42	723	10	1%
20	-35	-2	-33	759	12	2%
MEAN*	-8	-17	-51	716	11	2%
SD	30.7	27.5	27.3	39.7	2.5	0.3%

Two-way ANOVAs were completed on each of the five parameters associated with the modeled MRE. The factors used were subjects (20) and groups (9). There were significant differences between subjects for all parameters of the model. The only significant differences were between groups (# of points) for the overall error values of the model. To determine which groups were significantly different, two separate hypothesis tests were performed. These tests only compared the master file of 1800 points to the other groups. There were no comparisons made among the subset groups. A two-sample T-test found no significant differences ($\alpha = 0.05$). A Wilcoxon Rank Sum Test found significant differences between 1800 points and the first trial of 600 points and between 1800 points and the third trial of 600 points ($\alpha = 0.05$).

Shown in Figure 1 is a plot of the mean error for each zone of the MRE. The model error is low in the mid-region of the MRE (< 5mm) and increases significantly (>25 mm) in the outer regions of the envelope.

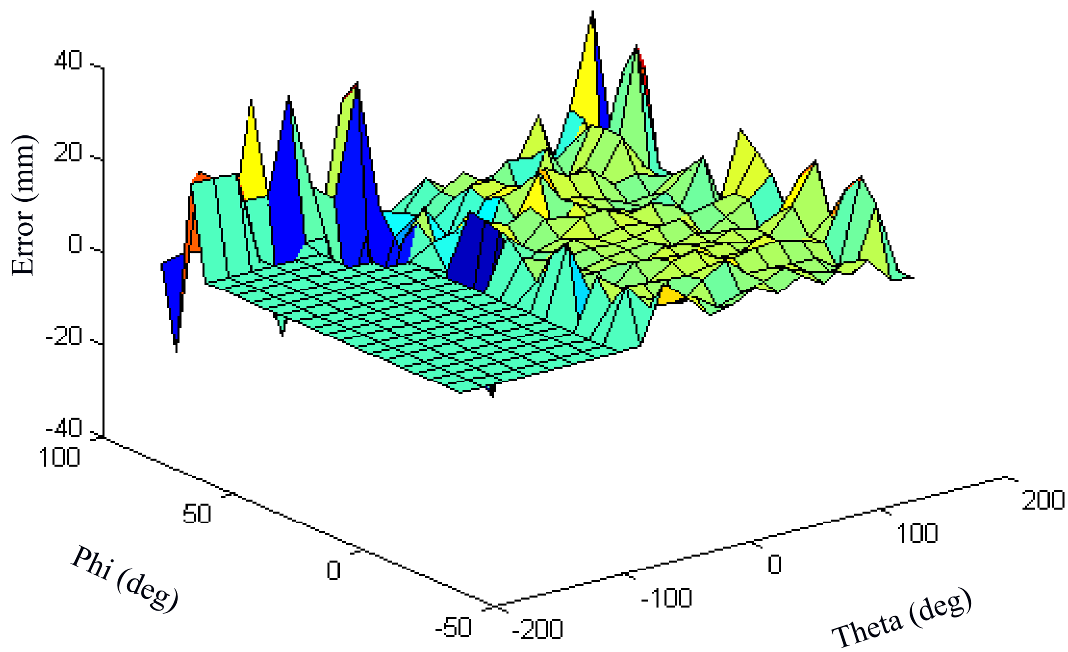

Figure 1: Plot of the model error (mm) in the various regions of the MRE.

DISCUSSION

Farley (1955) conceptualized the MRE as a simple sphere with a radius equal to the arm length of the operator. Sengupta and Das (2000) performed an empirical test of this conceptualization and found that a sphere did adequately describe the overall envelope. However, there remained additional concerns about the model which were the accuracy of the model throughout the entire envelope and the number of data points required to accurately determine the equation of the sphere. Based upon the findings of this study it is apparent that the spherical model performs better in the mid-region of the MRE than at the periphery. This finding is consistent with the general problems associated with Human-CAD models of reach which have difficulty predicting reaches in the outer borders of the reach envelope.

One of the major advantages of the spherical model is that it provides for a regular surface shape and should therefore require fewer data points than other techniques. This advantage was supported by this study where the number of data points was systematically decreased from 1800 to as few as 10 with no significant affect on the model parameters. This could mean that accurate MRE models could be achieved through simple data collection techniques.

CONCLUSIONS

1. The MRE can be sufficiently modeled as a sphere with as few as 10 maximum reach points.
2. Modeled spheres accurately predict near the center of MRE and show the greatest error in predicting at the extremes.
3. The origins of the spherical models are in the same general location relative to the acromion for all individuals.

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REFERENCES

1. Farley, R.R. (1955), *General Motors Engineering Journal*, **2**, 20-25.
2. MATLAB 5.0 (1996). User Guide, MathWorks Inc.
3. Sengupta, A.K. and B. Das (2000), Ergonomics 43(9) 1390-1404.