NC STATE UNIVERSITY

JTATM

JOURNAL OF TEXTILE AND APPAREL, TECHNOLOGY AND MANAGEMENT

Volume 5, Issue 1, Winter 2006

Developing Body Measurement Charts for Garment Manufacture Based on a Linear Programming Approach.

Deepti Gupta, Department of Textile Technology, Indian Institute of Technology, Hauz Khas, New Delhi –110016, India.
Naveen Garg, Department of Computer Science and Engineering, Indian Institute of Technology, Hauz Khas, New Delhi –110016, India.
Komal Arora and Neha Priyadarshini, Department of Computer Science and Engineering, Indian Institute of Technology, Hauz Khas, New Delhi –110016, India.

ABSTRACT

The process of developing body size charts for a given population is a highly complex one as too many variables are involved. The requirements are often contradictory as in trying to provide the best fit using a minimum number of sizes. With the availability of advanced mathematical tools it is now possible to address the issue as an optimization problem. In the present study, an algorithm based on the Linear Programming approach has been developed specifically to cluster a given population data into homogenous body size groups. The theoretical efficiency of the approach has been demonstrated on an anthropometric database of 1900 young Indian women. The mathematical tool developed is flexible enough to be adapted for use for mass production as well as mass customization of garments. It is extremely versatile in that garment specific size tables can be developed. The degree of fit desired at each body dimension as well as the body dimensions used as the basis of clustering can be changed with ease. It is also a great tool for inventory management as it gives exactly the number of people covered by each cluster thus giving the manufacturer and retailer the choice of deciding how many pieces to make in each style and in what sizes.

Keywords: Body Measurements, CAD, Garment Fit, Garment Sizing, Linear Programming, Optimization.

Introduction

The process of developing body size charts for garment manufacturers is a very complex one. In this paper, the development and testing of a novel mathematical solution based on the LP approach has been proposed. The results have been extensively validated mathematically, using the anthropometric database of a group of young Indian men and women. However, wearer trials need to be conducted for converting these body measurements into garment measurements. Further work is ongoing for developing a user friendly software based on the algorithm, for use by the garment manufacturing industry of India.

Background

A "size" is an item having specified measurements along certain dimensions, such that it will fit perfectly a person with measurements equal to that size (Tryfos, 1986). The purpose of an apparel sizing system is to divide a varied population into homogeneous subgroups. Members of a subgroup are similar to each other in body size and shape so that a single garment can adequately fit each of them. Members of different subgroups are dissimilar and would therefore require different garments (Ashdown & Delong, 1995). Fit of a garment depends on the correlation between garment measurements and the body measurements for which it is intended. In general, very little correlation exists among the human body measurements. Along with the large number of relevant body dimensions, the body proportions can also vary enormously. This is obvious from the variety of body shapes that can be seen in a group of people. Body size as well as body shape can be a characteristic of ethnic groups. Classifying a population into homogeneous body sizes is hence a highly complex problem.

The last decade has seen a remarkable surge in the number of studies reported on the subject from all over the world (McCulloch et al, 1998, Rifkin, 1994). Various statistical methods ranging from simple percentiles to complex combinations of multivariate and regression analyses have been employed for distribution of population into subgroups. More recently, powerful mathematical techniques have been employed with good results.

Gupta & Gangadhar, (2004) used Principal Component Analysis to identify the key body measurements which can form the basis for classifying a population data set. Body shapes and their distribution within the population were identified. Validation of size charts was achieved by calculating the aggregate loss of fit.

Tryfos, (1986) has suggested an integer programming approach to optimize the number of sizes so as to maximize expected sales or minimize an index of aggregate discomfort. He divides the space of body dimensions artificially into a set of discrete possible sizes. The probability of the sale of a garment from one company to a person falling in another category is modeled as a simple function of fit. The goal is then to choose the sizes in order to optimize sales of the garment. The problem is formulated as a “p median” or “Facility Location problem.”

A novel approach for the construction of apparel sizing systems has been proposed by McCulloch (McCulloch et al.1998). The concept of garment fit is captured by a distance measure, which is calculated from the discrepancies between the body measurements of an individual in the sample and the prototype design values of a size. Using this measure, known as aggregate loss, various existing sizing systems were compared (Ashdown, 1998). Non-linear optimization techniques were used to derive a set of possible sizing systems using multi-dimensional information from anthropometric data. Results showed that endogenous size assignment and selection of disaccommodated individuals together with relaxation of the requirement of a “Stepwise” size structure resulted in substantial improvements in fit over an existing sizing system.

Several approaches have been tried and tested as reported but what the industry is really looking for is a tool which can yield accurate, flexible and quick solutions to the extremely complex problem of what sizes to make and how many garments to make in each size. These values will vary from one geographical location to another even for the same retail chain. Customized size charts are thus required for each location to maximize the fit of garments for the intended clients and minimize inventories.

It is obvious that linearly graded sizing systems that range from very small to very large cannot cover a diverse population adequately. Human bodies come in all shapes and sizes and it is not possible to divide them on the basis of simple averages which lead to unrealistic sizes corresponding to the so called “standard” or “ideal” body measurements. What is needed is a completely random system, which can yield an optimum number of body sizes reflecting the true body measurements and proportions existing in the target population. The sizes thus obtained can be expected to provide the best possible fit for garments.

Furthermore, it would be advantageous to provide the users with the ability to choose their target population. Thus if a certain business manufactures clothes for young adults, it would be logical to do the clustering only for the data corresponding to the target group in the population rather than using the complete data set for adult women.

All this necessitates the development of a clustering algorithm, which, since it would have to be invoked frequently, has a small running time. All these requirements make the clustering problem all the more challenging. Bearing these considerations in mind, the problem of sizing in the current study was modeled with the objective of developing:

a) A suitable clustering algorithm for dividing population database into a predetermined number of homogenous size groups.
b) A system with an in-built flexible fit function to minimize the deviation of proposed measurements from the actual body dimensions.
c) A system such that the largest possible fraction of the population can be accommodated in minimum number of sizes.
d) A system which allows development of sizes for sub groups of population with ease and accuracy.

The fit-function (i.e. the tolerance or range) also depends to a great extent on the garment chosen. For instance, if the garment is a woman's skirt with an elastic band at the waist then the fit function for the waist measurement can be comfortably large.

Linear Programming

A *Linear Programming* problem is a special case of *Mathematical Programming* problem. From an analytical perspective, a mathematical program tries to identify an *extreme* (i.e., minimum or maximum) point of a functio $(x_1,x_2,\ldots,x_n)$, which furthermore satisfies a set of constraints, e.g., $g(x_1,x_2,\ldots,x_n) \geq b$. Linear programming is the specialization of mathematical programming to the case where both, function f - to be called the *objective function* - and the problem constraints are *linear*.

An important factor for the applicability of the mathematical programming methodology in various application contexts, is the computational tractability of the resulting analytical models. Under the advent of modern computing technology, this tractability requirement translates to the existence of effective and efficient algorithmic procedures which can provide a systematic and fast solution to these models.

The general form for a Linear Programming problem is as follows:

Objective Function:

$$\max/\min f(X_1,X_2,\ldots,X_n) := c_1 X_1 + c_2 X_2 + \ldots c_n X_n \qquad (1)$$

Technological Constraints:

$$a_{i1}X_1 - a_{i2}X_2 - \ldots + a_{in}X_n \begin{pmatrix} \le \\ = \\ \ge \end{pmatrix} b_i, \quad i = 1,\ldots,m \qquad (2)$$

Sign Restrictions:

$$(X_j \ge 0) \text{ or } (X_j \le 0) \text{ or } (X_j \text{ urs}), \quad j = 1,\ldots,n \qquad (3)$$

where "urs" implies *unrestricted in sign*.

The functions involved in the problem objective and the left-hand-side of the technological constraints are *linear*. It is the assumptions implied by linearity that to a large extent determine the applicability of the above model in real-world applications.

Another approximating element in many real-life LP applications results from the so called *divisibility* assumption. This assumption refers to the fact that for LP theory and algorithms to work, the problem variables must be *real*. However, in many LP formulations, meaningful values for the levels of the activities involved can be only *integer*. Introducing integrality requirements for some of the variables in an LP formulation turns the problem to one belonging in the class of *(Mixed) Integer Programming (MIP)* which have been shown to belong to the notorious class of *NP-complete* problems (problems that have been ``formally'' shown to be extremely "hard" computationally). Given the increased difficulty of solving IP problems, sometimes, in practice, near optimal solutions are obtained by solving the LP formulation resulting by relaxing the integrality requirements - known as the *LP relaxation* of the corresponding IP - and (judiciously) rounding off the fractional values for the integral variables in the optimal solution.

Specifically, we shall define as the *feasible region* of the LP of Equations 1 to 3, the entire set of vectors $< X_1, X_2, \ldots, X_n >^T$ that satisfy the technological constraints of Eq. 2 and the sign restrictions of Eq. 3. An *optimal* solution to the problem is any feasible vector that further satisfies the optimality requirement expressed by Eq. 1.

The points covered by each data entry taken as a potential garment size was calculated. The linear problem was solved using GLPSOL LP-SOLVER to maximize the number of points covered. However, the solution to the linear program is a fractional solution that cannot be used directly to obtain garment sizes.

In this paper, we report the development of an algorithm for finding the body sizes so as to accommodate the maximum number of individuals under the constraints imposed by the fitness function. To obtain garment sizes which cover a large proportion of the population, we developed a greedy algorithm along the lines of the classical algorithm for set-cover. Our algorithm is iterative in nature; in each step it picks that potential garment size which "covers" the largest number of uncovered points. The algorithm stops when it has picked the number of sizes permitted.

We compared the efficiency of our algorithm against the highest possible number of individuals in which can be theoretically accommodated (theoretical upper bound) in the chosen number of sizes. These values were determined by solving an existing linear program (using an LP Solver). We tested the algorithm on a data set of 2000 Indian males and 1900 Indian females with 20 body measurements each and found that in most instances the algorithm, which is very fast in practice, came very close to the upper bound values yielded by the LP solver.

Materials and Methods:

Anthropometric Data

A data set comprising of body measurements for 1900 Indian women (18 to 35 years) has been used for the study. The anthropometric survey was conducted on behalf of a leading garment brand of India across six cities in India. Twenty measurements were taken for each individual.

The approach

Three approaches were used for clustering the population. The approach 1 yielded the theoretical optima possible for a given set of variables. Approach 2 was the algorithm specially written for this application and approach 3 was used to validate the results. These are described below:

1. **An LP solver-** GLPSOL was used to determine the maximum (theoretical) number of points that could be covered under a given number (say n) f sizes.

2. **Algorithm development**: Given an arbitrary fit function, an algorithm was written to cluster the population into a predetermined number of sizes (1-20) so as to maximize the number of individual accommodated.
3. **Grid Approach**: In this system each point was considered in a grid of predetermined granularity as a potential garment size and the number of points in the data set covered by that size was calculated. The process was repeated to get the required number of sizes.

The three approaches were tested on women's' top and lower body measurements. Fit functions were changed to see how the coverage of data was affected in each case.

Results and discussion

Multiple correlation analysis of the data conducted earlier (Gupta and Gangadhar, 2004) showed that there was poor correlation between the length and girth measurements. However, good correlation existed between the major girth dimensions namely bust, hip and waist and within the length measures. For developing body size charts, a judicious combination of the girth and length measures is thus required. It determined that better fit could be obtained in garments, if the size classification was done separately for the top body and the lower body. For the purpose of analysis, lesser is the number of body measurements taken for clustering, larger would be the population covered under each size.

The algorithm allows the use of any selected measurements as the basis of clustering. In the present work clustering for the lower body garments was done on the basis of hip, waist (girth) and outer leg length (length) measures. Clustering for top body garments was done on the basis of bust (girth), cervical height and waist from Centre front (length measures). Size charts were generated using four different fit functions namely (i) **+1, -1," (ii) +1, -0.5," (iii) +1.5, - 0.5" and (iv) +2,- 1."** In each case, output was taken using all the three approaches mentioned above. Results obtained are reported and discussed below.

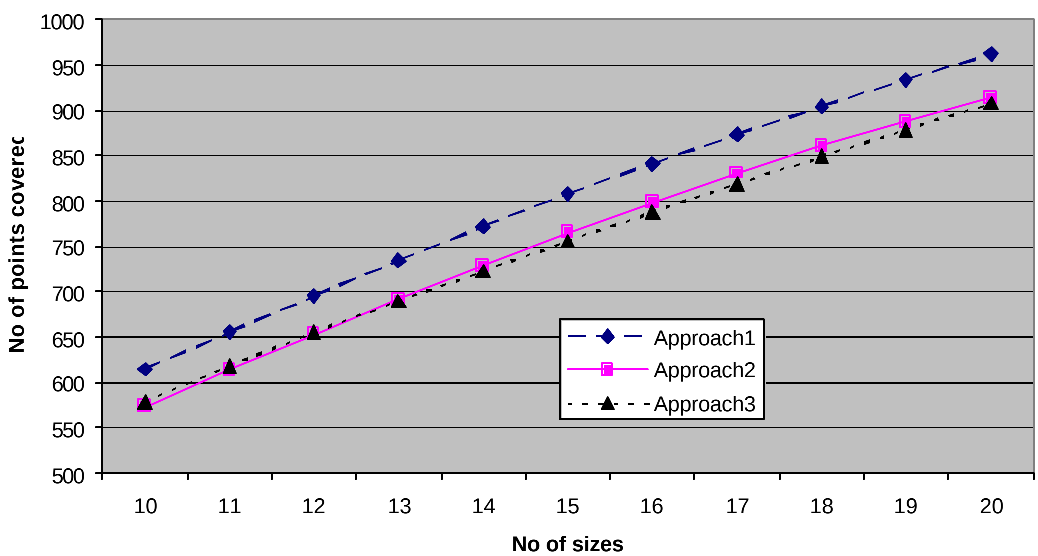
Case 1. Fit Function = +1, -1" **(**i.e. point * is covered by the size if size-1< point <size+1 for all dimensions). Table I shows the size chart obtained using fit function of ± 1."

Table I. Size chart for 20 sizes using fit function of ± 1”

No. of sizes	Body measurements			Points covered	% Cover
	Hip	Waist	Length		
1	30	22	60	26	1.4
2	30	24	62	39	3.16
3	31	23	63	33	5.44
4	31	24	59	50	8.22
5	32	24	61	88	13.11
6	32	25	63	61	16.5
7	32	26	60	48	19.16
8	33	25	60	28	20.72
9	34	28	62	32	22.5
10	34	26	62	87	27.33
11	34	27	60	68	31.11
12	34	25	64	38	33.22
13	34	28	64	37	35.27
14	35	28	59	38	37.38
15	36	26	61	27	38.88
16	36	27	63	45	41.38
17	36	28	62	60	44.72
18	36	28	64	30	46.38
19	37	30	61	41	48.66
20	38	30	63	40	50.88
Total				**916**	**51**

It can be seen from Table 1 that if there was to be only one size for the given data set, then only 26 (1.4%) persons (out of 1900) would be covered if the fit function was defined as $\pm$ 1." However, as the number of sizes increases to 10, 27% of population is covered, while with 15 sizes 39% are covered and with 20 sizes 51% of the population was covered. Comparison of the results obtained by three approaches is shown in Fig. 1. In all cases, the values obtained by approach 2 and 3 fall within 5-10% of the theoretical upper bound value obtained by Approach 1.

Figure 1. Number of points covered by three approaches (FF)



Note: FF = Fit Function

Sizes in Table I have been arranged in the ascending order of hip measurements. There are two size options each for women having hip measurement equal to 30 and 31" and one size each or hip measure equal to 35, 37 and 38" respectively. For hip size 34" there are 4 options while for hip 36" there are 5 options. The distribution clearly shows that unlike the empirical systems in practice, this system is completely random and truly reflects the distribution of measurements in a given data set. To illustrate, look at the five sizes having hip of 34." In these sizes, the difference between the hip and waist ranges from 6" to 9" meaning that all different body proportions corresponding to different body shapes (**each point of data refers to a person in the population)* are being catered. Difference in length measurements is also reflected in the size chart. For example, Size 12 is for a taller woman having a narrower waist as compared to size 11.

The 3D and 2D plots of the proposed sizes superimposed over the actual population data are shown in Figures 2-4. In all cases, the cover of population was seen to be quite good. Data sets having extreme values are not covered by the system. Special sizes may have to be developed for such people who have odd dimensions and proportions.

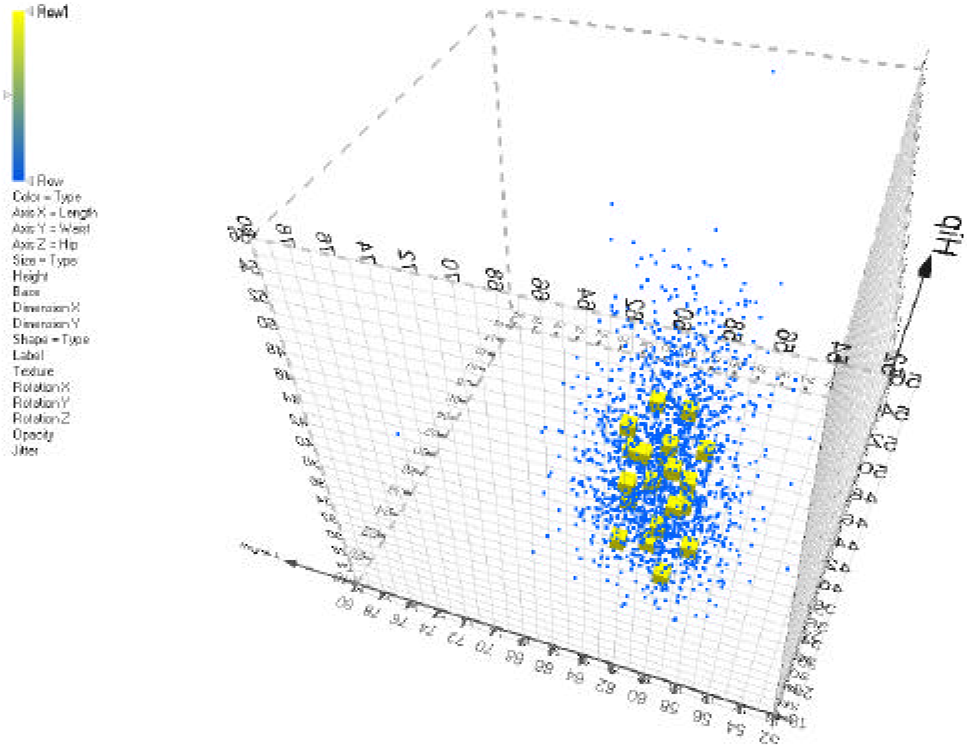


Figure 2. 3D A plot showing the proposed sizes superimposed over the population measurements for hip, waist and length.

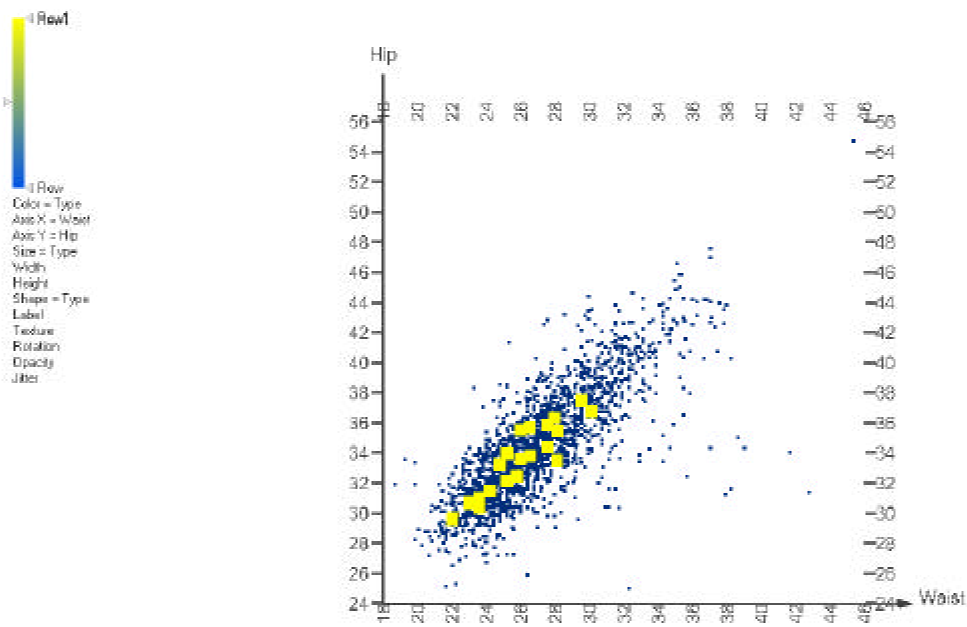


Figure 3. 2D A plot showing the proposed size measurements for hip and waist superimposed over the data measurements.

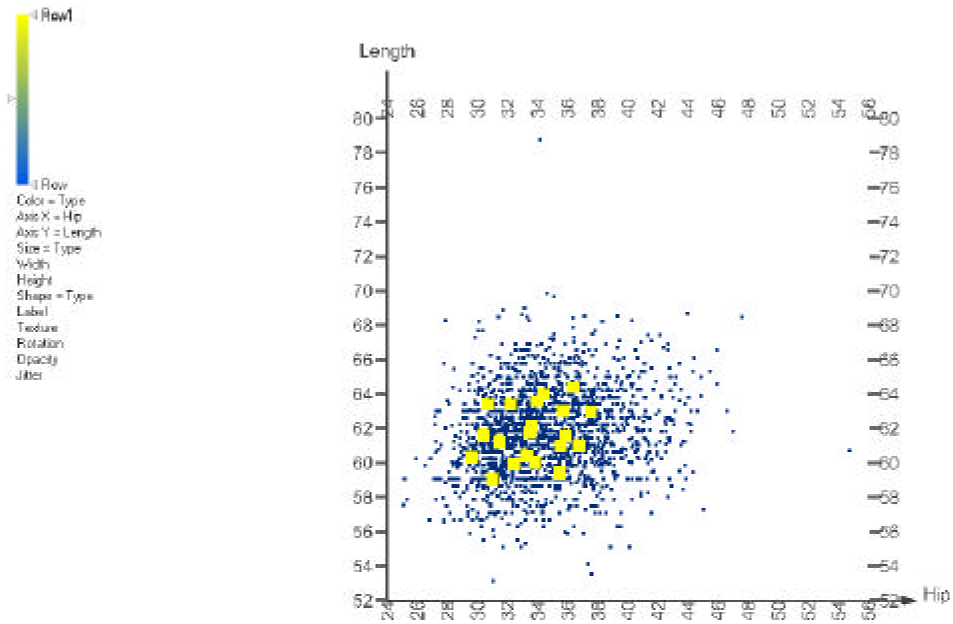


Figure 4. 2D A plot showing the proposed size measurements for hip and length superimposed over the data measurements.

Case 2. Fit function = +1, -0.5, i.e. point is covered by the size if size-0.5<point<size +1. The proposed size chart is shown in Table II. As expected, the number of people covered by this function is less than that covered by Case 1. There is a consistent reduction of about 30-40% in cover for a given number of sizes and a 40% reduction in total cover with only 31% of the population being covered under 20 sizes. A completely different set of sizes is obtained in this case as compared to Case 1. For example, the 4 sizes for hip 36" have an identical waist measure of 27" but vary significantly in the length measure.

Table II. Size chart for 20 sizes using fit function of + 1,” -0.5.”

No. of sizes	Body measurements			Points covered	% Cover
	Hip	Waist	Length		
1	30	24	61	23	1.27
2	30	22	60	23	2.55
3	31	24	59	28	4.11
4	31	24	61	45	6.61
5	32	24	62	41	8.88
6	33	26	60	32	10.66
7	33	25	63	37	12.72
8	33	24	60	21	13.88
9	33	25	62	45	16.38
10	34	27	62	25	17.77
11	34	24	63	19	18.83
12	34	27	60	36	20.83
13	35	26	63	29	22.44
14	35	29	60	18	23.44
15	36	27	65	20	24.55
16	36	27	60	22	25.77
17	36	27	62	29	27.38
18	36	27	63	19	28.44
19	37	30	61	24	29.77
20	37	29	62	21	30.94
Total				**557**	**31**

Case 3. Range = + 1.5, - 0.5, i.e. point is covered by the size, if size-0.5<point<size +1.5 for all dimensions. Results are shown in Table III. It is interesting to note that with this fit function the overall range of hip measurements covered is more than the previous cases. Hip measurements from 29” to 39” are covered, even though the total population covered is slightly less than that in case 1. There is only one size for hip 36” in this case.

Table III. Size chart for 20 sizes using fit function of + 1.5,” -0.5.”

	Body measurements			Points covered	% Cover
No. of sizes	Hip	Waist	Length		
1	29	22	60	24	1.33
2	30	23	61	30	3
3	31	23	60	51	5.83
4	31	24	63	40	8.05
5	31	24	61	80	12.5
6	32	25	59	29	14.11
7	32	25	63	54	17.11
8	33	26	60	62	20.55
9	33	25	62	88	25.44
10	33	27	63	36	27.44
11	33	28	60	29	29.05
12	34	25	64	31	30.77
13	35	26	59	29	32.38
14	35	27	61	55	35.44
15	35	26	62	45	37.94
16	35	28	60	40	40.16
17	36	27	65	36	42.16
18	37	30	61	39	44.33
19	37	28	63	35	46.27
20	39	31	63	25	47.66
Total				**858**	**47.7**

Case 4 Range = +2, -1, i.e. point is covered by the size if size-1<point<size+2 for all dimensions. Results are reported in Table IV. There is a significant improvement in the total covered under this fit function with 81% of the population being covered. The range of measurements covered is wider as expected.

Table IV. Size chart for 20 sizes using fit function of + 2," - 1."

No. of sizes	Body measurements			Points covered	% Cover
	Hip	Waist	Length		
1	29	22	59	33	1.8
2	30	23	63	59	4.5
3	30	23	61	151	12.9
4	30	24	57	43	15.3
5	31	26	61	29	16.9
6	32	25	58	92	22
7	32	24	64	99	27
8	32	25	61	224	40
9	33	24	61	37	42
10	34	27	63	48	44.7
11	34	27	60	100	50.2
12	34	25	59	26	51.7
13	35	27	62	161	60.6
14	35	27	65	77	64.9
15	36	29	59	51	67.7
16	37	30	62	102	73.4
17	38	28	60	24	74.7
18	38	29	63	27	76.2
19	39	32	63	33	78.1
20	40	31	61	50	80.8
Total				1466	81

Conclusions

It has been possible to demonstrate through this work the potential of an algorithm developed by us for clustering a population into homogenous groups which can be fitted within a pre-determined number of garment sizes. The fit function for each measurement can be varied. It can be different for each measurement depending upon the criticality of fit desired at a particular body area. It is possible to change the measurements and the number of measurements used for clustering.

One of the strongest points in favor of this system is that it tells exactly the number of people falling under each size category. This allows a retailer or a manufacturer to choose the sizes of interest to them and know in advance how many pieces to manufacture and stock. These numbers would vary from one store location to other and can be worked out exactly for each country/ state or location.

This is the first step in the process of development of a garment sizing system for the Indian population. The tool can be modified to suit the requirements of ready made garment mass production as well a mass customization. Investigators are further collecting up-to-date anthropometric data an analyzing body shape and proportions in the Indian population. Work is ongoing to determine the fit functions required for each body measurement for each garment type. Fitness trials will be conducted to establish the fit preferences of Indian women leading to development of digitized pattern drafts to suit the various Indian figure types.

References

1. Ashdown S. P. and Delong M, App. Ergo., Vol. 26 (1), p 47 (1995)
2. Ashdown SP, IJCST, Vol. 10(5), p 324 (1998)
3. Gupta D and Gangadhar B R, IJCST, Vol.16 (5) 2004, 458-469
4. McCulloch CE, Paal B. and Ashdown SP, J. Opl. Res. Soc., Vol. 49, p 492 (1998)
5. Rifkin G, The New York Times, Dec.8.1994, A1, D4.
6. Tryfos P, J.Opl Res. Soc. Vol.37 (10), p1001(1986).