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Factors Affecting Apparel Pattern Grading Accuracy: Existing Software Solutions Comparison and Development of New Solution

Dejavniki, ki vplivajo na natančnost gradiranja krojev oblačil: primerjava obstoječih programskih rešitev in razvoj nove rešitve

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Abstract
Every so often, grading is not 100% accurate due to the conventional system for calculating the grading increment. The aim of this study was to develop a new calculation system of grading increment provided by different software, e.g. Lectra, Gerber, Optitex, Boke CAD etc., and to develop a new mathematical solution that enhances grading precision. For this experiment, three different spec sheets of different buyers were collected, and then combined and drawn to a solitary sketch for both front and back including all points of measures (POM) for a more easy comparison. The solutions for the presence of diagonal and curve measurements were provided with examples using various tools and techniques of different professional garment CAD software. The benefit of the new approach is not only reduced errors of grading but also guaranteed garment fit without distorting style features. However, the drawbacks of the measurement method are complicated and time-consuming. They revolve around the fact that iterative fitting and adjustments are mandatory to improve the fit before bulk production. The study revealed that this new system slightly increases calculation time, whereas the sample approval time for order execution reduces considerably.
Keywords: grading, CAD, pattern making, grading system, Pythagoras grading

Izvleček
Gradiranje pogosto ni 100-odstotno natančno zaradi konvencionalnega sistema za izračun gradirnega prirastka. Namen te študije je razviti nov sistem izračunavanja gradirnega prirastka v primerjavi s tistimi, ki jih ponujajo različna programska orodja, kot so Lectra, Gerber, Optitex, Boke CAD ipd., in razviti novo matematično rešitev, ki izboljša na-

tančnost gradiranja. Za raziskavo so bile izbrane tri tehnične skice različnih proizvajalcev, združene v eno samo skico oblačila, ki prikazuje sprednji in zadnji del oblačila ter vključuje vse mere oblačila za njihovo lažjo primerjavo pri gradiranju. Nato so na primerih z uporabo različnih orodij in tehnik gradiranja z različnimi komercialnimi programi CAD PDS prikazani rezultati gradiranja diagonalnih in krivuljnih mer. Prikazana prednost novega pristopa gradiranja ni le v zmanjšanju napak pri gradiranju, temveč tudi v zagotavljanju prileganja oblačila, ne da bi se spremenila njegova oblika. Pomanjkljivost tega pristopa je v zapleteni in dolgotrajni merilni metodi, ki za izboljšanje rezultata gradiranja zahteva ročno prilagajanje gradirnega prirastka.

Ključne besede: gradiranje, CAD, konstruiranje krojev oblačil, gradirni sistem, Pitagorovo gradiranje

1 Introduction

Grading is a process of increasing and decreasing pattern dimensions by creating multiple sizes to fit different people [1–3]. In the concepts of pattern grading, it has been described that the grading system is developed from sizing specifications, and sizing specifications are derived from anthropometric surveys [4]. In order to create garments in each size, the increases used to create each new pattern should be based on body measurements associated with that specific size and organised in a size chart. In the late 1960s, computerised grading was developed in the USA, followed by Germany, Italy, Denmark, UK and France to improve the accuracy as well as efficiency [3, 5]. The basic principle of computerised grading is the same as manual grading. The manual procedure of grading is exceptionally tedious and grading efficiency is affected by the grader's experience [6]. The computer was used as a drawing tool. Computerised grading was still tedious and time-consuming; however, the mistake-vulnerable grading process was done satisfactorily with the computerised method. Computer-aided pattern grading systems have become popular in clothing factories as they have become faster, more consistent and accurate, more reliable and manageable than conventional manual grading [7–10]. Generally, grading contains three steps, i.e. determining grade points, determining alteration rules and amounts of each grade point, and joining altered points using the curve smoothing technique [11, 12]. A grade rule can be determined by comparing and calculating mathematical or geometrical differences between the body measurements of each size [1, 13–15]. A grade rule table defines how far each cardinal point of pattern moves in the x and y direction in a Cartesian graph [16]. The way towards grading is extremely dreary and requires an incredible level of acumen and discernment, and frequently the exactness of the graded pattern pieces of clothing is affected by the grader's skills [17]. The proportion of the pattern will vary according to the experience, accuracy and personal judgment of the grader [18]. The problems of assessing the factors affecting apparel pattern grading accuracy were identified and some recommendations were proposed in the first part of this work [19]. This paper, however, focuses on the comparison of different solutions to achieve grading accuracy provided by different software, e.g. Lectra, Gerber, Optitex, Boke CAD etc., and develops a new mathematical explanation. Grading has long remained a neglected area of research in the clothing industry and the classical size charts used by the industry have evolved over the years with a trial-and-error method [20]. Pattern grading is a procedure of efficiently enhancing and reducing the measurements of a piece or sloper into a different number of sizes for large scale manufacturing [4, 17]. The amount and direction into which the pattern increases or decreases has been determined. At the same time, the correct proportions of garments have been maintained without distorting the style features. In order to grade a pattern, increases (or decreases) are applied at specific points of a pattern to make each new pattern in another larger (or smaller) size. The conventional incremental computerised grading is based on a Cartesian graph that has the horizontal (x) and the vertical axes (x) that intersect at right angles and divide an area into four quadrants. In the Cartesian graph, the dimensional changes of patterns are moved to the left or right on the x-axis, and up or down on the y-axis to create new sizes [10, 21]. Consequently, horizontal increments are placed on the x-axis and vertical measurements on the y-axis. Diagonal measurement increments are based on the assumption that they will increase in the same amount as the amount on the x- or y-axis. Nevertheless, scientifically this is not true and will lead to measurement problems. Again, during the grading of the curve line, the amount that should change in the x and y directions to get the desired length of the curve is unknown and complex. Hence, grading increments must be changed more than once until the required curve length is achieved. As it can be seen in the first part of this paper, different problems arise due to the presence of diagonal and curved lines in a spec sheet [22, 23]. The problem is in the calculation method; therefore, the calculation should be done properly to minimise grading errors. The presence of diagonal and the presence of curve measurements are only two major problems. Their presence in the spec sheet leads to other problems, as it affects the selection of base size, number of sizes present in the spec sheet etc. If they can be avoided, then other problems will be automatically minimised. For instance, if there is no diagonal measurement, then whatever the base is selected, it will not lead to grading errors. In some spec sheets, it is possible to avoid diagonal and curve measurements but not in all types of product spec sheets. Therefore, solutions to these problems are highly needed.

2 Experimental design

2.1 Materials

For this experiment, three different spec sheets of different buyers were collected, combined and drawn to a solitary sketch for both front and back (cf. Figure 1 and Table 1), including all points of measures (POM) to compare them more easily. The measurement points and their descriptions of all three spec sheets are shown in Table 1.

2.2 Methods

The solutions for the presence of diagonal and curve measurements are provided below with examples using different tools and techniques of professional garment CAD software, e.g. Lectra, Optitex, Gerber, Tuka CAD, Boke CAD. If these CADs are not available and are techniques unknown to the grader, then another mathematical solution was developed by the authors, which is not only applicable in software but also in the manual process. It is called "Pythagoras Grading" as authors use the "Pythagoras formula" to calculate new grading increment values. All techniques are described and compared with the existing or conventional grading system. Finally, some recommendations are given to choose which solution should be used in what situation.

The conventional system is based on the increment of the given measurement of apparel for different sizes, e.g. "body length from high point shoulder" is increased by 2 cm for each size; hence, points H and G should increase by 2 cm in the negative y direction. For the T-shirt specs A, B and C, cardinal points (represented by A, B, C, E, G, H for front and back, and A, B, C, D, E, F, G for sleeve) and Cartesian coordinate values of grading increments are shown in Figure 2.

3 Experimental work

To solve the grading error due to the presence of diagonal and curve measurements, there are different solutions possible, which are described below.

3.1 Solutions to problem 1 – presence of diagonal measurements

3.1.1 Solution 1 to problem 1 – manual manipulation of grading increment

When grading is required in a particular point, an increment only from the base size to the next higher size is calculated. However, there are two problems

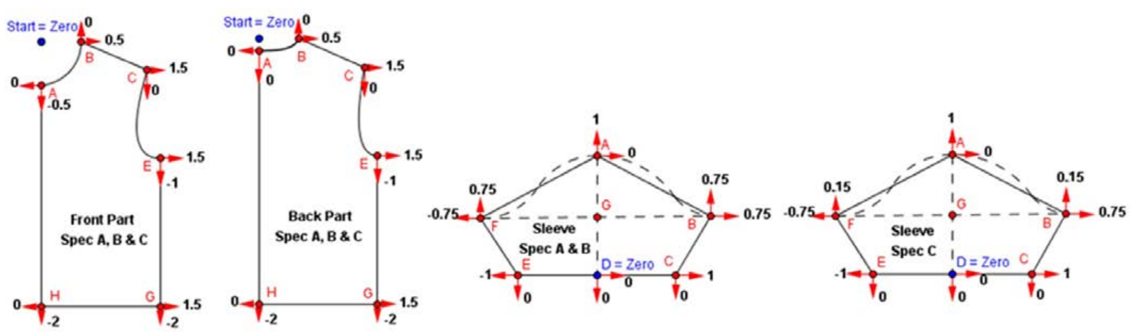

Figure 2: Cardinal points and Cartesian coordinate values of T-shirt specs A, B and C

Table 1: Measurement points and their descriptions of all three specification sheets

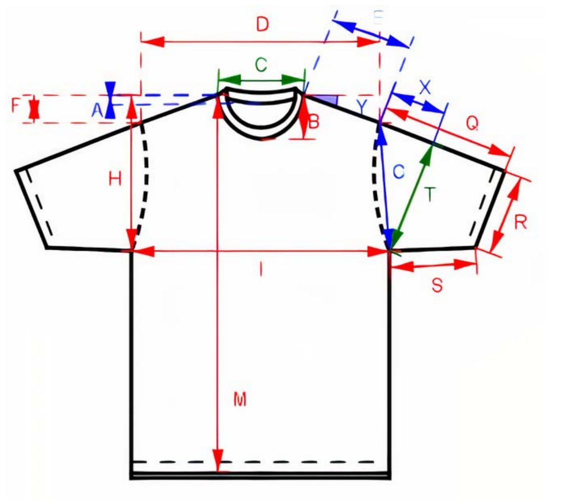

Figure 1: Combination of all measurement points of T-shirt

Points	Description	POMs
A	Back neck drop or depth	BND
B	Front neck drop or depth	FND
C	Neck width or opening	NW
D	Across shoulder width or shoulder to shoulder	AS
E	Shoulder length	S
F	Shoulder drop or slant	SD
G	Armhole straight	AHS
H	Armscye depth	ASD
I	Half chest	HC
M	Body length from high point shoulder	BLfHPS
Q	Sleeve length	SL
R	Sleeve opening	SO
S	Under sleeve	US
T	Sleeve width or upper arm	SW
X	Sleeve cap height	SCH
Y	Shoulder slant in degree	SSD

POM	Reference spec A					Reference spec B					Reference spec C				
	S	M	L	XL	XXL	S	M	L	XL	XXL	S	M	L	XL	XXL
BND	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
FND	8.00	8.50	9.00	9.50	10.00	8.00	8.50	9.00	9.50	10.00	8.00	8.50	9.00	9.50	10.00
NW	16.00	17.00	18.00	19.00	20.00	16.00	17.00	18.00	19.00	20.00	16.00	17.00	18.00	19.00	20.00
AS	–	–	–	–	–	45.00	48.00	51.00	54.00	57.00	45.00	48.00	51.00	54.00	57.00
S	15.00	16.00	17.00	18.00	19.00	15.00	16.00	17.00	18.00	19.00	–	-	-	-	-
SD	5.00	5.00	5.00	5.00	5.00	–	–	–	–	–	5.00	5.00	5.00	5.00	5.00
AHS	24.00	25.00	26.00	27.00	28.00	24.00	25.00	26.00	27.00	28.00	–	-	-	-	-
ASD	–	–	–	–	–	–	–	–	–	–	29.00	30.00	31.00	32.00	33.00
HC	48.00	51.00	54.00	57.00	60.00	48.00	51.00	54.00	57.00	60.00	48.00	51.00	54.00	57.00	60.00
BLf-HPS	70.00	72.00	74.00	76.00	78.00	70.00	72.00	74.00	76.00	78.00	70.00	72.00	74.00	76.00	78.00
SL	21.00	22.00	23.00	24.00	25.00	21.00	22.00	23.00	24.00	25.00	21.00	22.00	23.00	24.00	25.00
SO	18.00	19.00	20.00	21.00	22.00	18.00	19.00	20.00	21.00	22.00	18.00	19.00	20.00	21.00	22.00
US	14.00	14.50	15.00	15.50	16.00	–	–	–	–	–	–	-	-	-	-
SW	–	–	–	–	–	23.00	23.75	24.50	25.25	26.00	23.00	23.75	24.50	25.25	26.00
SCH	–	–	–	–	–	–	–	–	–	–	9.55	10.40	11.25	12.10	12.95

Note: All units are measured in cm. POM: Points of measure

with that. One is that it is assumed that any horizontal or vertical increment leads to an increase in the same amount in diagonal measurement, which is scientifically not true. For instance, when shoulder length increased e.g. by 1 cm and half neck width by 0.5 cm, then the horizontal increment would be (1 + 0.5 = 1.5 cm) in case of "spec A" and the vertical increment 0 cm as there is no increment in shoulder drop. According to the conventional system, the horizontal increment for shoulder length of spec A is 1.5 cm for all sizes. However, an increment of 1.5 cm in the horizontal direction does not mean that the diagonal (shoulder length) increment would be the same. After the grading, it was found that the measurements are lower than required. Manually, the measurements are initially increased by 0.01 cm in the horizontal direction until the required length is achieved. From the result, it was established that at least 0.04 cm should increase along with 1.5 cm measurement, meaning that instead of the 1.5 cm horizontal increment, it should increase by 1.54 cm. And for other sizes, it may be 1.53 or 1.55, since the shoulder angle is not constant. Even if shoulder length increased constantly, e.g. 1 cm (15, 16, 17, 18 and 19 cm for S, M, L, XL and XXL sizes, respectively), the increment should not be the same as the angle of the shoulder for all sizes is not constant, which represents the second problem. To prove this, size spec A of the T-shirt is graded with conventional calculation and then the measurement error is checked, which is shown in Figure 3. After that manual manipulation in grading, the increment is done to rectify the measurements, which is shown in Figure 4. Before and after manipulation measurements for the shoulder are shown below in Figures 3 and 4 along with their grading increment values.

Based on Figures 3 and 4, it can be said that if the diagonal measurement exists in a spec sheet, then the measurement checking and manual manipulation in grading increment should be done to rectify the measurements.

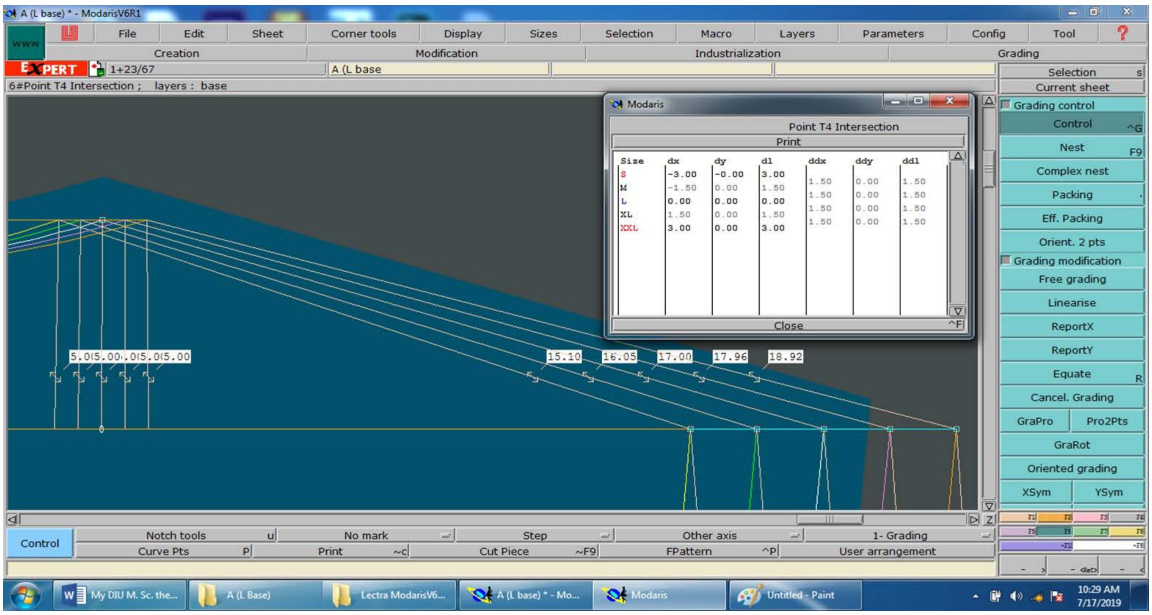

Figure 3: Shoulder length measurements and their grading increment values before manipulation (spec A)

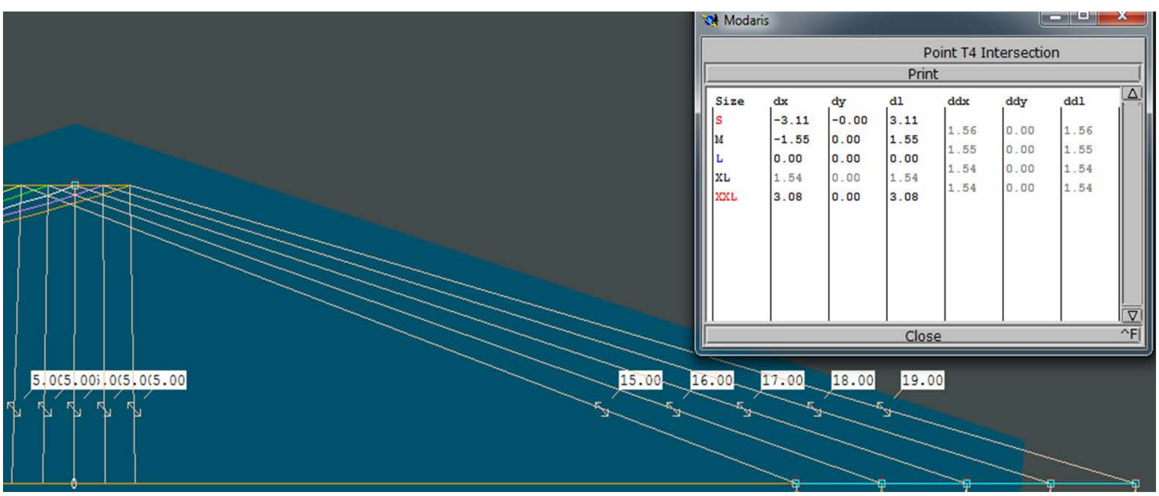

Figure 4: Shoulder length measurements and their grading increment values after manipulation (spec A)

3.1.2 Solution 2 to problem 1 – segment editing with Optitex or TukaCAD

Manual manipulation is time-consuming; therefore, different software companies provide different solutions for grading rectification, e.g. "measure and segment editor" in Optitex and TukaCAD software. The shoulder length before measurement and segment editing is designated in Figure 5, and after measurement and segment editing is given in Figure 6.

In segment editing, the "last horizontal" option is chosen since shoulder length can only increase or decrease in the horizontal direction. If the vertical option is chosen, then the shoulder drop measurement will change. The selection of the segment editor option depends on the measurement location, e.g. in spec A of the T-shirt, shoulder length and shoulder drop are given. The shoulder drop change has to plot in the vertical direction and the shoulder length change has to plot in the horizontal direction. In the case of spec B of the T-shirt, shoulder length and across shoulder are given. Hence, the across shoulder change has to plot in the horizontal direction and the shoulder length change has to plot in the vertical direction. In this case, the "last vertical" option must be chosen in the segment ed-

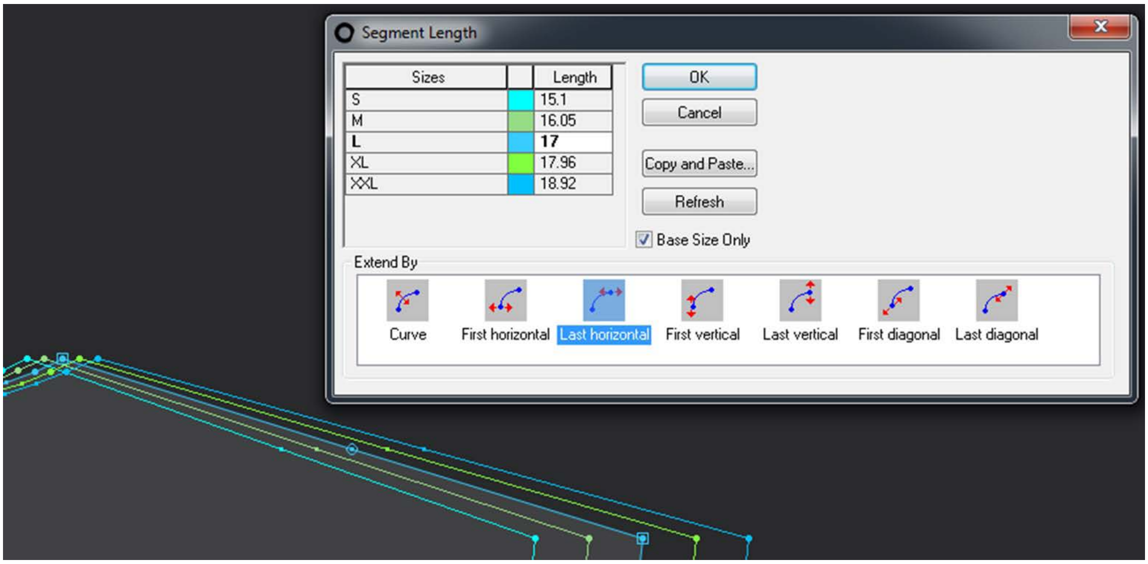

Figure 5: Shoulder length before segment editing (spec A)

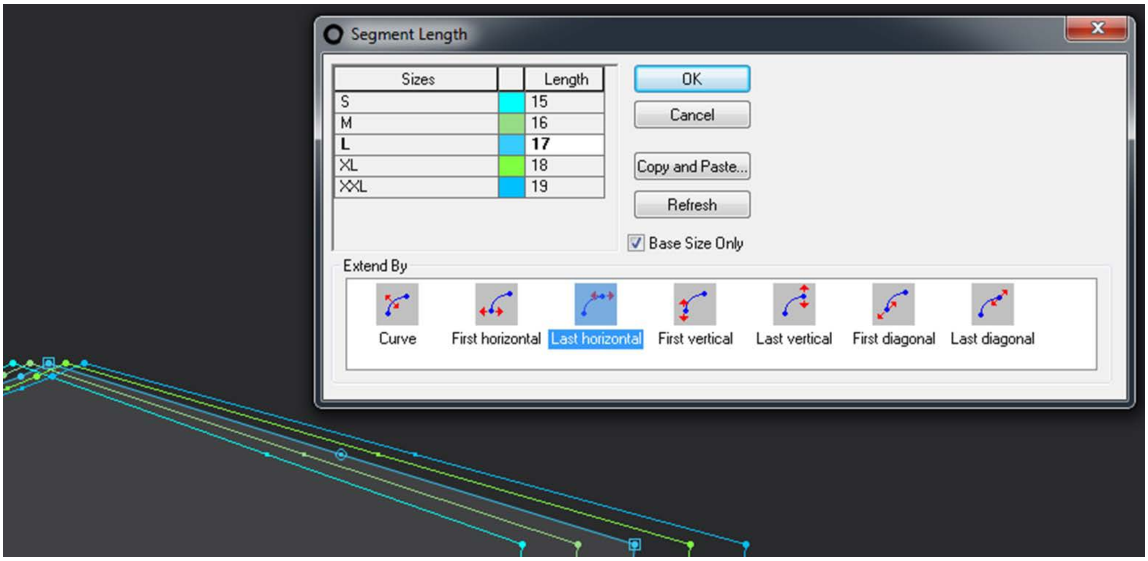

Figure 6: Shoulder length after segment editing (spec A)

itor. Another reason for choosing "last vertical or last horizontal" instead of "first horizontal or first vertical" is due to the shoulder point being the last point and side neck point being the first point of the shoulder line, and in Optitex or Tuka CAD software, points are counted in the clockwise direction. After segment editing, it was established that there is no diagonal grading error.

3.1.3 Solution 3 to problem 1 – automatic grading with BokeCAD

Automatic grading is available only in BokeCAD as far as the authors know. There is a difference between automatic grading and conventional Cartesian coordinate grading. In Cartesian coordinate grading, firstly, a base should be selected and a pattern should be drawn according to the base size measurements. Then, the grading increment calculation is done according to the given measurements

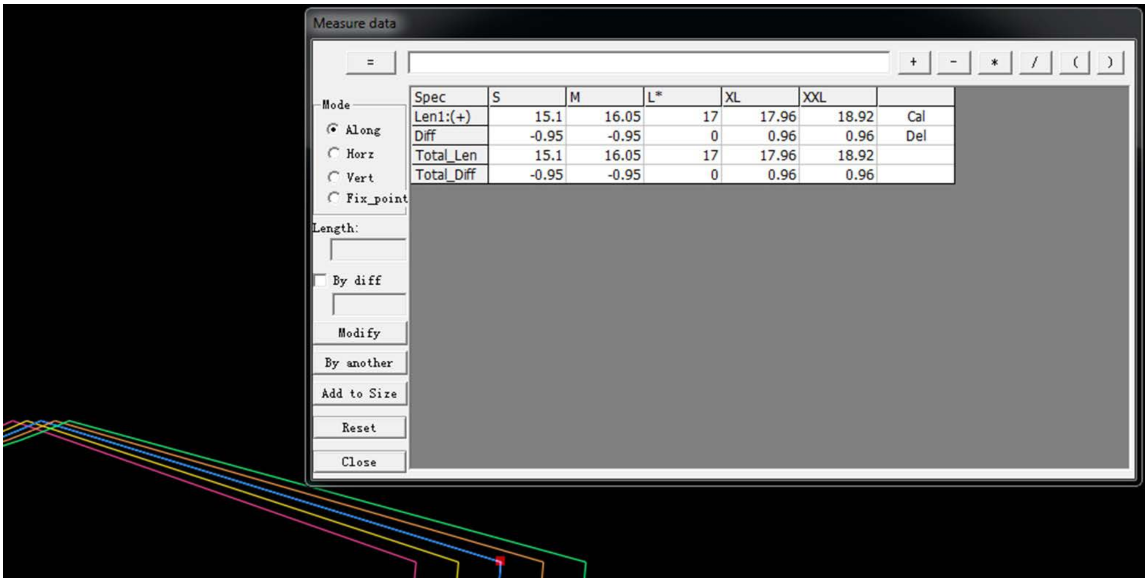

Figure 7: Shoulder length after conventional grading (spec A) with BokeCAD

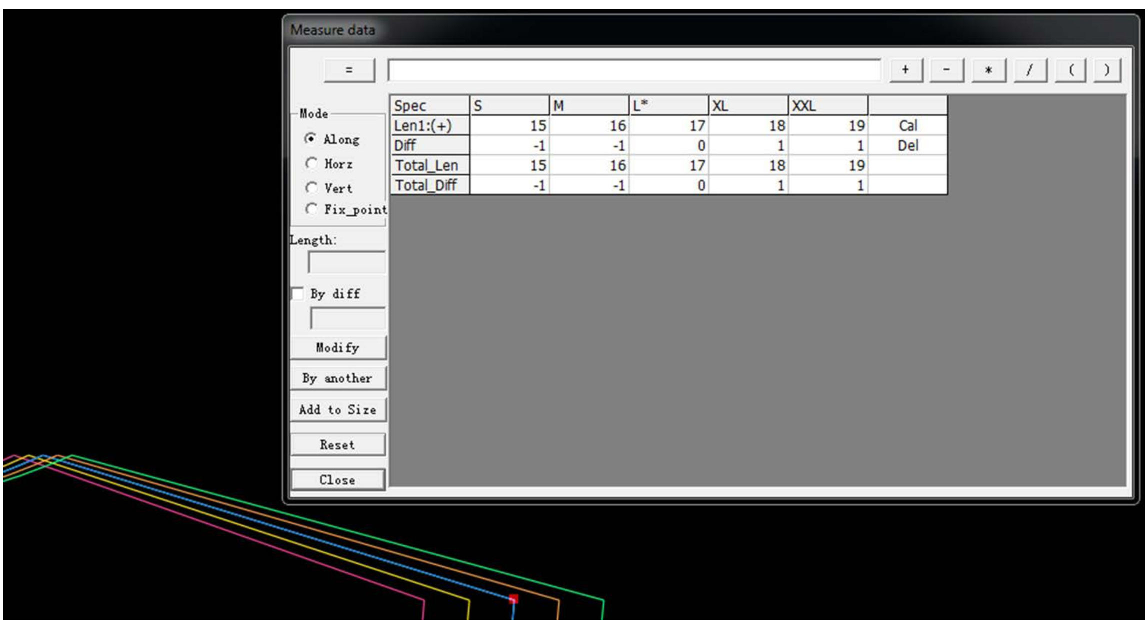

Figure 8: Shoulder length after automatic grading (spec A) with BokeCAD

in the size chart and their input in the x and y directions of the Cartesian coordinate grading. However, in automatic grading, the first whole measurements from the spec sheet should be plotted in the size chart of the software. Then, a base size should be selected and a pattern drawn by the measurement points not by the measurements. When the grading button is clicked, it will automatically grade the whole pattern. The advantages of the system are: a) grading increment calculation is not needed, hence no possibility of miscalculation; b) diagonal measurements are automatically adjusted, hence manual manipulation is not needed for the diagonal grading rectification; c) curve grading is almost accurate, as sometimes up to 0.02 cm grading error is found in the case of curve line grading, which is negligible.
For the experiment, "spec A" of T-shirts was selected and graded with both conventional Cartesian coordinate (x, y) grading and automatic grading method. The results are shown in Figures 7 and 8. From Table 2, it can be seen that graded measurements are more precise after automatic grading than conventional grading.

3.1.4 Solution 4 to problem 1 – Pythagoras grading system

It was seen that the diagonal measurements grading increments create grading errors. To minimize the latter, a new grading increment calculation system was developed. For this experiment, specs A and B of T-shirts were selected. The details follow below:

Table 2: Diagonal length comparison of body part (spec A) with conventional and automatic grading of BokeCAD

Point of measures	Measurement comparison	Size					Unit
		S	M	L	XL	XXL	
Shoulder	Error after conventional grading	+0.10	+0.05	0.00	−0.04	−0.08	cm
	Length acquired after conventional grading	15.10	16.05	17.00	17.96	18.92	
	Length required	**15.00**	**16.00**	**17.00***	**18.00**	**19.00**	
	Length acquired after automatic grading	15.00	16.00	17.00	18.00	19.00	
	Error after automatic grading	0.00	0.00	0.00	0.00	0.00	
Armhole straight	Error after conventional grading	+0.01	+0.01	0.00	0.00	0.00	cm
	Length acquired after conventional grading	24.01	25.01	26.00	27.00	28.00	
	Length required	**24.00**	**25.00**	**26.00***	**27.00**	**28.00**	
	Length acquired after automatic grading	24.00	25.00	26.00	27.00	28.00	
	Error after automatic grading	0.00	0.00	0.00	0.00	0.00	
*Note: * indicates base size*							

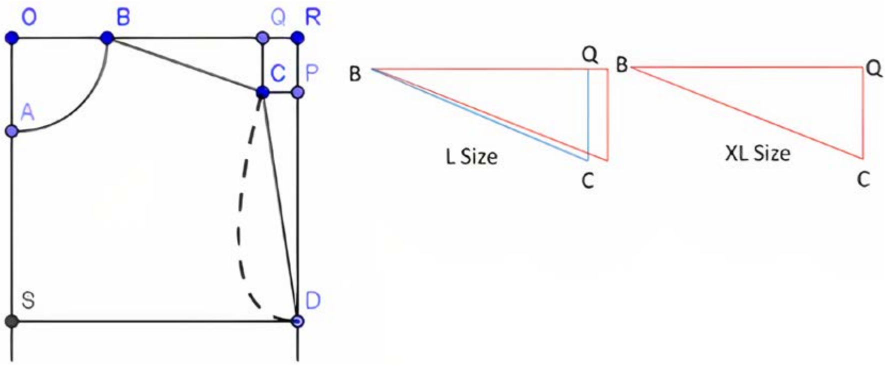

Figure 9: Points to calculate Pythagoras grading for pattern pieces of T-shirt body part (spec A)

(a) Pythagoras grading for pattern pieces of T-shirt body part (spec A)

Pattern construction of a T-shirt body part can be divided into some geometries that are shown in Figure 9.

From Δ BQC (cf. Figure 9), according to Pythagoras law:

$$BQ^2 + QC^2 = BC^2 \quad (1),$$

for L size:

$$Q_L = \sqrt{{BC_L}^2 - {QC_L}^2} = \sqrt{17^2 - 5^2} = 16.25 \quad (2),$$

and for XL size:

$$BQ_{XL} = \sqrt{{BC_{XL}}^2 - {QC_{XL}}^2} = \sqrt{18^2 - 5^2} = 17.29 \quad (3).$$

The x-axis value of shoulder point C = (17.29 – 16.25) + (x-axis change in B point) = 1.04 + 0.5 = 1.54, and y-axis value of shoulder point C = 0 (due to no change in shoulder drop). According to conventional calculation, C = (1, 0) which should be replaced with (1.54, 0).

From Figure 9, OR = SD = ¼ chest; QC = RP = shoulder drop;

$\therefore CP_L = QR_L = OR_L - OB_L - BQ_L = (¼\ \text{chest})_L - (½\ \text{neck width})_L - BQ_L$

$\therefore CP_L = 27 - 9 - 16.25 = 1.75$

and $CP_{XL} = QR_{XL} = OR_{XL} - OB_{XL} - BQ_{XL} = (¼\ \text{chest})_{XL} - (½\ \text{neck width})_{XL} - BQ_{XL}$

$\therefore CP_L = 28.5 - 9.5 - 17.29 = 1.71$

From Δ CPD (cf. Figure 9), according to Pythagoras law:

$$PD^2 + CP^2 = CD^2 \quad (4),$$

for L size:

$$PD_L = \sqrt{26^2 - 1.75^2} = 25.94 \quad (5),$$

and for XL size:

$$PD_{XL} = \sqrt{27^2 - 1.71^2} = 26.95 \quad (6).$$

The x-axis value of armpit point D = 1.5 (due to change in ¼ chest) and the y-axis value of armpit point D = 25.94 – 26.95 = –1.01.

According to conventional calculation, D = (1.5, –1) which should be replaced with (1.5, –1.01).

After applying Pythagoras grading, the grading increment values of T-shirt body parts are changed, as shown in Figure 10.

After the grading with new grading increments of points C and D, the measurements found are presented in Table 3.

From Table 3, it can be seen that after applying Pythagoras grading, errors were minimised considerably.

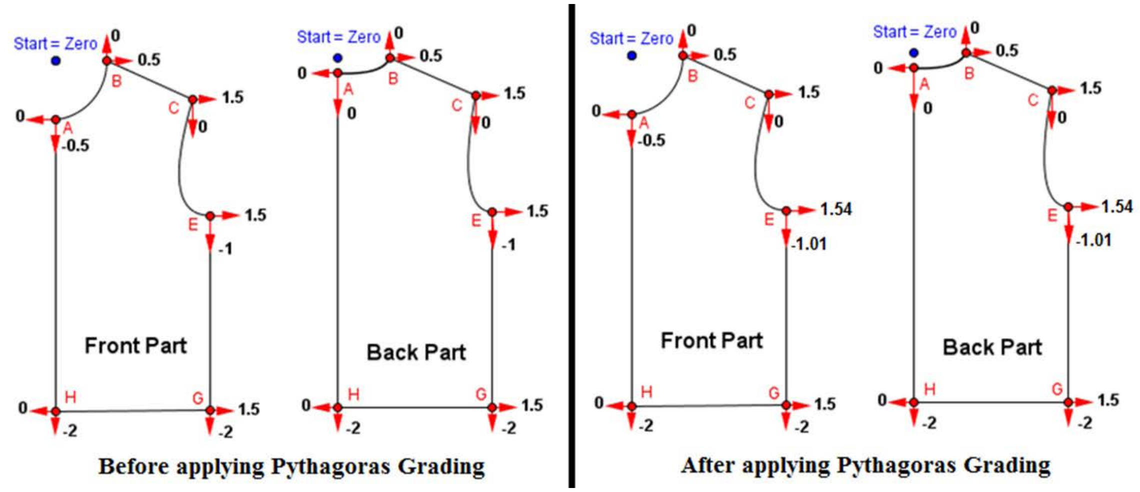

Figure 10: Grading increment of spec A for pattern pieces of T-shirt body parts before and after Pythagoras grading (L size as base size)

Table 3: Diagonal length comparison of pattern pieces of T-shirt body parts (spec A) before and after applying Pythagoras law

Point of Measures	Measurement comparison	Size					Unit
		S	M	L*	XL	XXL	
Shoulder	Error before applying Pythagoras law	+0.10	+0.05	0.00	−0.04	−0.08	cm
	Length acquired before applying Pythagoras law	15.10	16.05	17.00*	17.96	18.92	
	Length required	**15.00**	**16.00**	**17.00***	**18.00**	**19.00**	
	Length acquired after applying Pythagoras law	15.02	16.01	17.00*	18.00	19.00	
	Error after applying Pythagoras law	+0.02	+0.01	0.00	0.00	0.00	
Armhole straight	Error before applying Pythagoras law	+0.01	+0.01	0.00	0.00	0.00	cm
	Length acquired before applying Pythagoras law	24.01	25.01	26.00*	27.00	28.00	
	Length required	**24.00**	**25.00**	**26.00***	**27.00**	**28.00**	
	Length acquired after applying Pythagoras law	24.00	25.00	26.00*	27.01	28.01	
	Error after applying Pythagoras law	0.00	0.00	0.00	+0.01	+0.01	

*Note: * indicates base size*

(b) Pythagoras grading for the pattern pieces of T-shirt body part (spec B)

From Δ BQC (cf. Figure 9), according to Pythagoras law:

$$BQ^2 + QC^2 = BC^2 \quad (7),$$

where $BQ_L = OQ_L - OB_L$ = (half across shoulder – half neck width) of size L = 25.5 – 9 = 16.5.

For L size:

$$QC_L = \sqrt{BC_L{}^2 - BQ_L{}^2} = \sqrt{17^2 - 16.5^2} = 4.09 \quad (8)$$

and for XL size:

$$BQ_{XL} = \sqrt{18^2 - 17.5^2} = 4.21 \quad (9).$$

The y-axis value of shoulder point C = (4.09 – 4.21) = –0.12 and the x-axis value of shoulder point C = 1.5 (due to change in across shoulder), hence the grading increment value of C = (1.5, –0.12) instead of traditional (1.5, 0.).

From Δ CPD (cf. Figure 9), according to Pythagoras law:

$$CD^2 + PD^2 = CD^2 \quad (10),$$

where CD = armhole straight and CP = QR = OR – OQ = (¼ chest – ½ across shoulder).

Therefore,

$$PD_L = \sqrt{CD_L{}^2 - CP_L{}^2} = \sqrt{26^2 - 1.5^2} = 25.96 \quad (11)$$

and

$$PD_{XL} = \sqrt{CD_{XL}{}^2 - CP_{XL}{}^2} = \sqrt{27^2 - 1.5^2} = 26.96 \quad (12).$$

The y-axis value of armpit point D = (25.96 – 26.96) + y-axis point of C = (–1 – 0.12) = (–1.12) and the x-axis value of armpit point D = 1.5 (due to change in ¼ chest), hence the grading increment value of D = (1.5, –1.12) instead of traditional (1.5, –1).

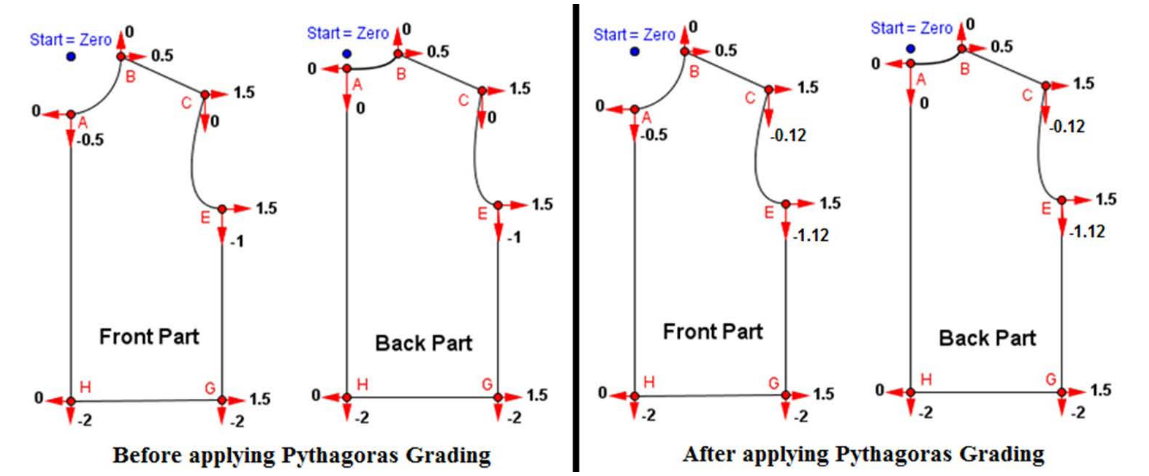

Figure 11: Grading increment of pattern pieces of T-shirt body parts (spec B) before and after Pythagoras grading (L size as base size)

After applying Pythagoras grading, the graded measurements were changed, as it can be seen in Table 4.

Figures 10 and 11, and Tables 3 and 4 show that Pythagoras grading can be used for higher precision grading for diagonal lines.

3.2 Solutions to problem 2 – presence of curve measurements

3.2.1 Solution 1 to problem 2 – segment measuring and manual manipulation of grading increment value

In the first part of the paper [19], it can be seen that the back and front sleeve curves do not match with

Table 4: Diagonal length comparison of pattern pieces of T-shirt body parts (spec B) before and after applying Pythagoras law

Point of measures	Measurement comparison	Size					Unit
		S	M	L*	XL	XXL	
Shoulder length	Error before applying Pythagoras law	+0.07	+0.03	0.00	–0.03	–0.05	
	Length acquired before applying Pythagoras law	15.07	16.03	17.00*	17.97	18.95	cm
	Length required	**15.00**	**16.00**	**17.00***	**18.00**	**19.00**	
	Length acquired after applying Pythagoras law	15.00	16.00	17.00*	18.00	19.00	
	Error after applying Pythagoras law	0.00	0.00	0.00	0.00	0.00	
Armhole straight	Error before applying Pythagoras law	0.00	0.00	0.00	0.00	0.00	cm
	Length acquired before applying Pythagoras law	24.00	25.00	26.00*	27.00	28.00	
	Length required	**24.00**	**25.00**	**26.00***	**27.00**	**28.00**	
	Length acquired after applying Pythagoras law	24.00	25.00	26.00*	27.00	28.00	
	Error after applying Pythagoras law	0.00	0.00	0.00	0.00	0.00	

*Note: * indicates base size*

the front and back armhole curve length in the conventional grading system. As the armhole straight is

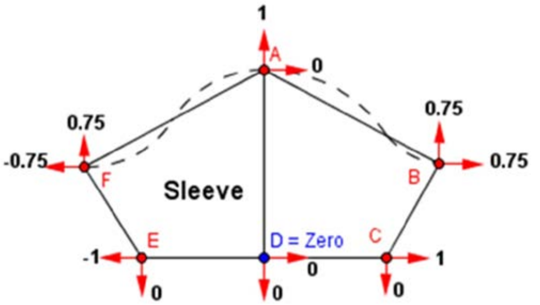

Figure 12: Grading increment for sleeve of T-shirt (spec B) in conventional system

given, after shape correction, armhole curve lengths cannot be modified. Sleeve curves must be manipulated until they match the curve lengths of front and back armhole curves.

For spec B, sleeve width and armhole straight are given. The x-axis of the "F" point (cf. Figure 12) cannot be modified. Instead, a fixed increment must be plotted as sleeve width is given. The y-axis must be modified until the curve length of "AF" (cf. Figure 12) matches the front armhole curve lengths.

Figures 13–16 show that if curve lengths need to match each other, the measurement checking and manual manipulation in grading increment should be conducted to rectify the measurements.

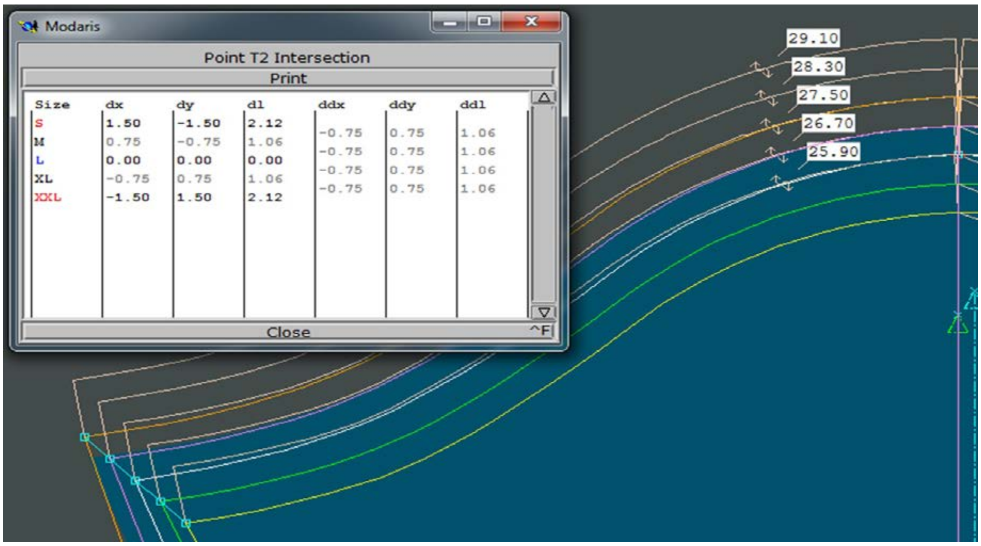

Figure 13: Front sleeve curve before manipulation of grading increment of point F (spec B)

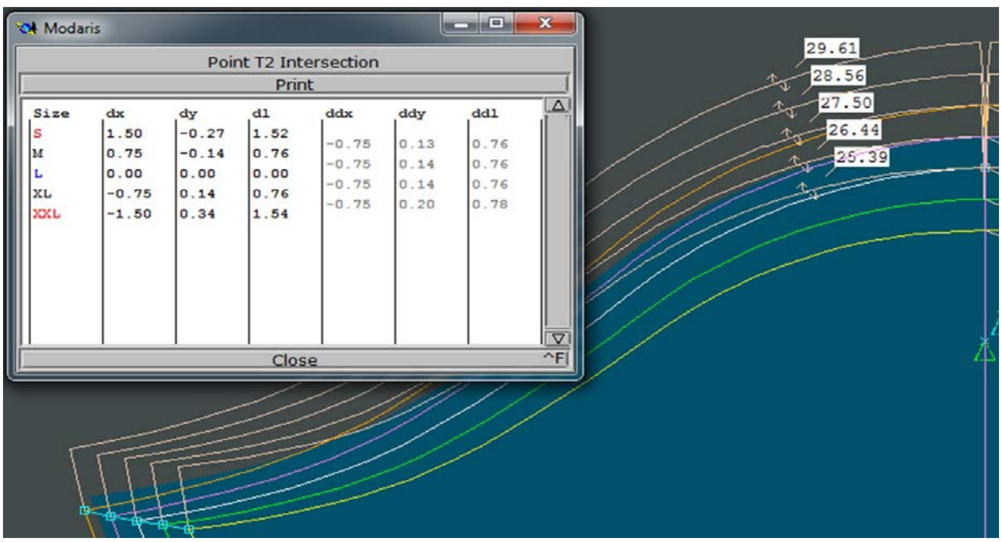

Figure 14: Front sleeve curve after manipulation of grading increment of point F (spec B)

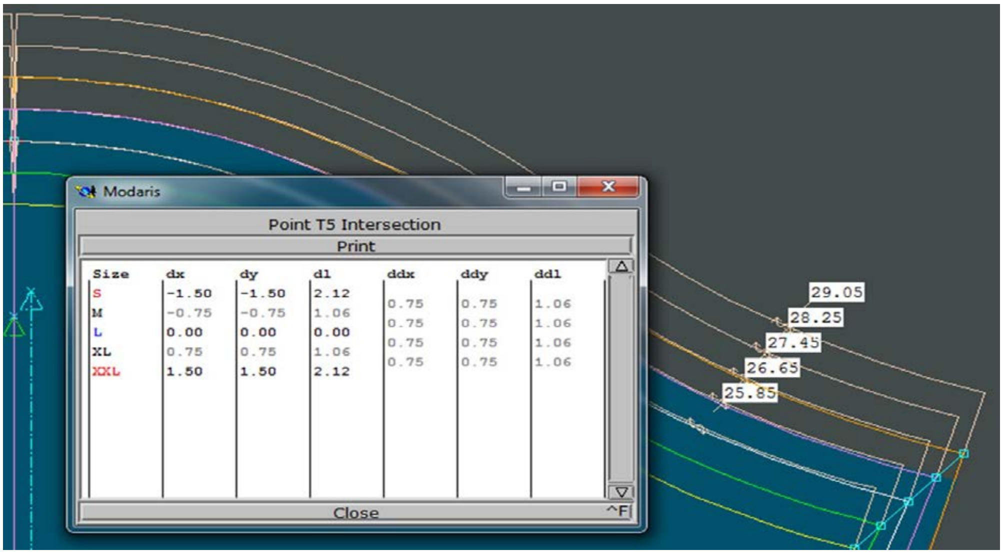

Figure 15: Back sleeve curve before manipulation of grading increment of point B (spec B)

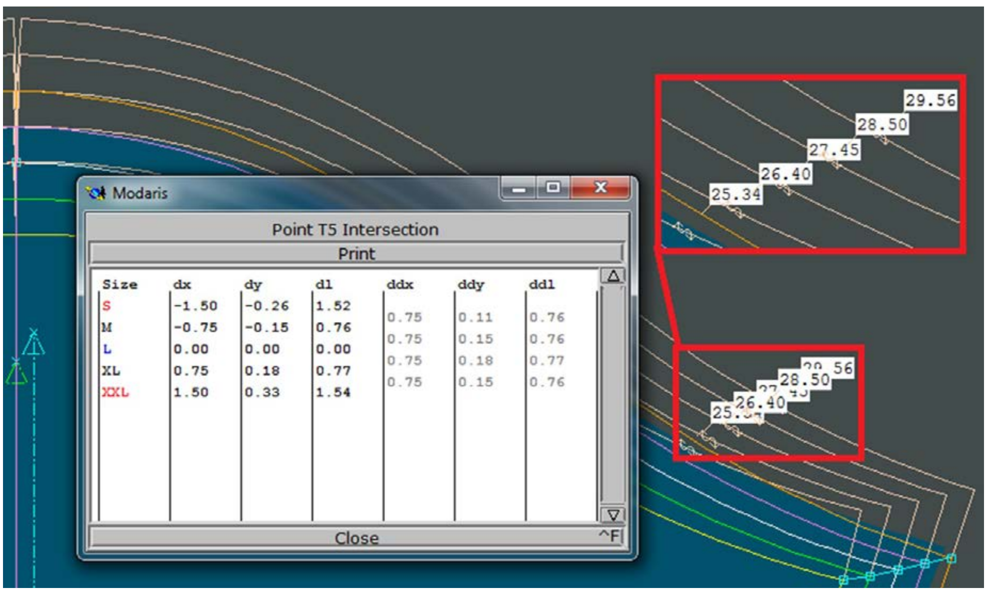

Figure 16: Back sleeve curve after manipulation of grading increment of point B (spec B)

However, in the case of spec A, this method cannot rectify the grading errors as the sleeve curve length measurement and under sleeve measurement are connected to only one point (F point in Figure 12). Any change in the x or y direction affects the other line. It can be said that if a combination such as "diagonal and vertical" or "diagonal and horizontal" or "curve and vertical" or "curve and horizontal" is given, then it is possible to rectify the grading with the "segment measuring and manual manipulation of grading increment value" technique. However, if the "diagonal and curve" or "diagonal and diagonal" combination is given, then it is not possible to solve the grading with the "segment measuring and manual manipulation of grading increment value".

3.2.2 Solution 2 to problem 2 – segment editing with Optitex or TukaCAD

Since manual manipulation is time consuming, different software companies provide a different solution for grading rectification, e.g. "measure and segment editor" in the Optitex and TukaCAD software. Before and after the measurement of the front and back sleeve curve before and after segment editing are presented in Figures 17–20.

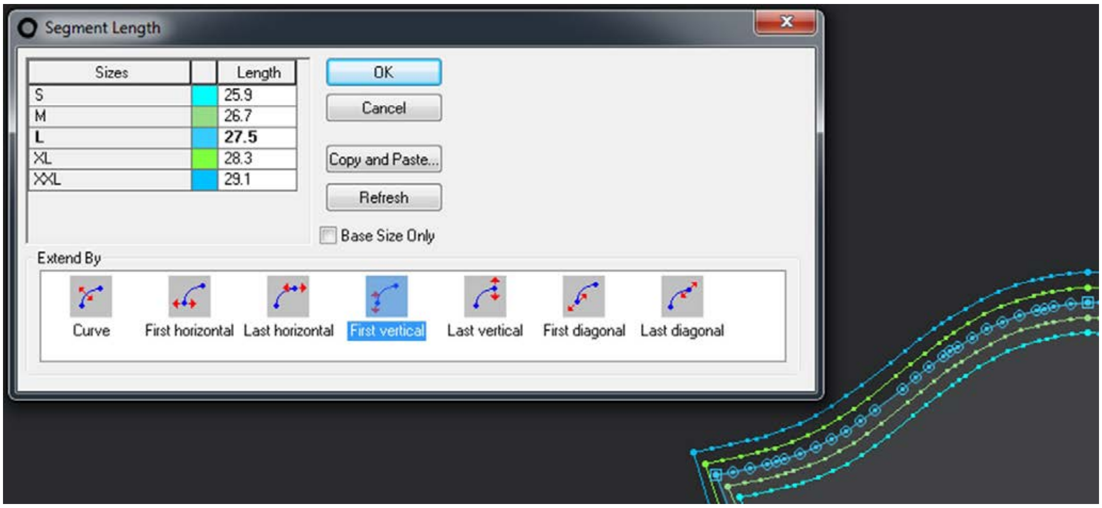

Figure 17: Front sleeve curve before segment editing (spec B)

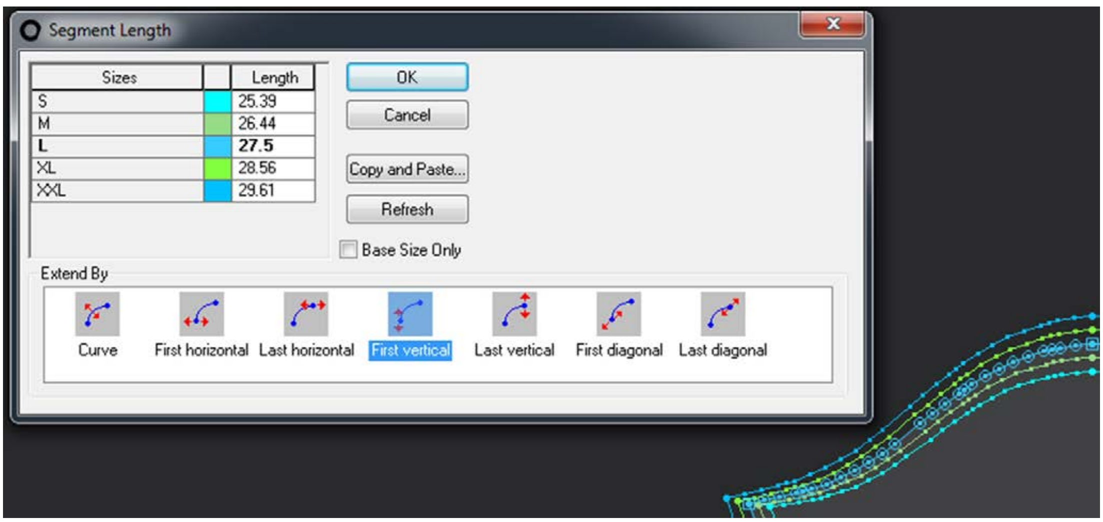

Figure 18: Front sleeve curve after segment editing (spec B)

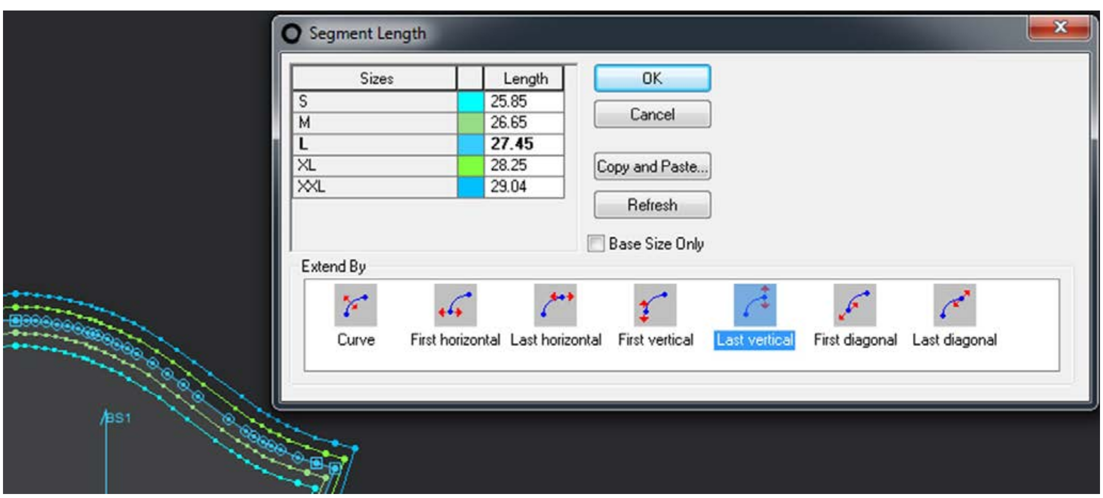

Figure 19: Back sleeve curve before segment editing (spec B)

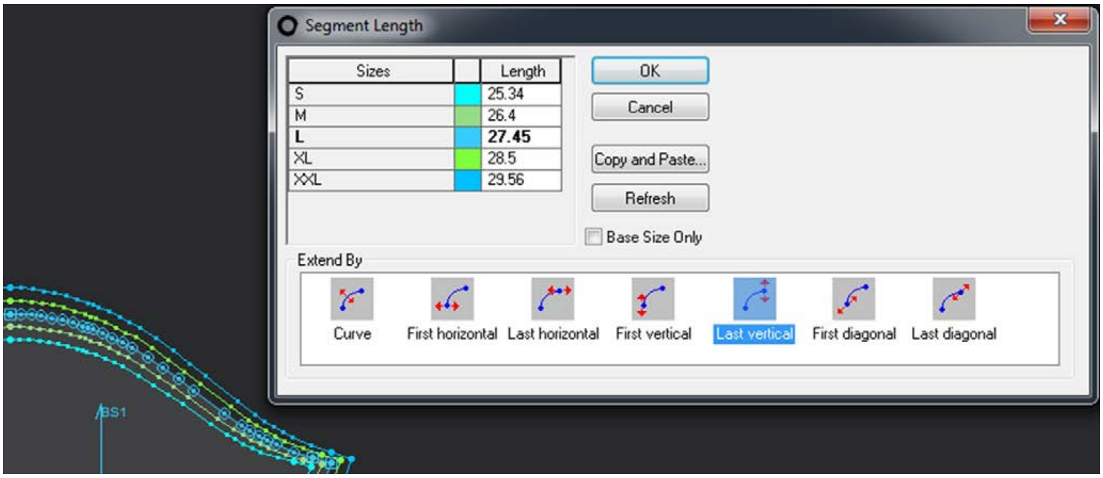

Figure 20: Back sleeve curve after segment editing (spec B)

In segment editing for the front sleeve curve (spec≈B), the "first vertical" option is chosen and for the back sleeve curve (spec B), the "last vertical" option is chosen, as in the Optitex or Tuka CAD software, points are counted in the clockwise direction. Moreover, it is possible to change front and back sleeve curve in the vertical direction since under sleeve is not given. It is not possible to select the horizontal direction as sleeve width is given in spec B. However, in the case of spec A, the segment editor cannot solve the error of sleeve curve length measurement and under sleeve due to them being connected to only one point (F point in Figure 12). Any change in the x or y direction affects the other line. It can be said that if a combination such as "diagonal and vertical" or "diagonal and horizontal" or "curve and vertical" or "curve and horizontal" is given, then it is possible to rectify the grading with the segment editor. However, if the "diagonal and curve" or "diagonal and diagonal" combination is given, then it is not possible to solve grading with the segment editor (cf. examples above).

3.2.3 Solution 3 to problem 2 – automatic grading with BokeCAD

Sometimes the spec sheet does not have any given curve length. However, due to the matching of some curve lengths, the front and back sleeve curve lengths should be matched with the front and back armhole curve lengths. Sometimes, the curve length depends on diagonal length, e.g. in spec B, armhole straight is 26 cm and after making the curve, the front and back armhole curve lengths are 27.50 cm and 27.45 cm, respectively. To get that length sleeve armhole straight, 27 cm (SAHS = AHS + 1 cm) were drawn to get 27.5 and 27.45 cm front and back sleeve curve lengths. However, this is not fixed. Only for this spec, 1 cm is added to the armhole straight to match the curve length. For another spec sheet, it will vary according to the measurement. Due to diagonal grading error, curve lengths changed as well. But even if the diagonal grading values are rectified, the curves do not match 100% with each other and a slight error will occur, the latter being negligible. For 100% matching of the curve, a slight modification is quite enough after automatic grading. Therefore, for the experiment, specs A and B of T-shirts were selected and graded with both the Cartesian coordinate (x, y) and automatic method. The results are presented in Tables 5–6.

Tables 5 and 6 show that after automatic grading, there is no diagonal grading error. And up to 0.1 cm, the grading error is found in curve-line grading, which is negligible.

3.2.4 Solution 4 to problem 2 – Pythagoras grading system

As it was seen, diagonal measurement and curve measurements related to diagonal measurement create grading errors. To minimize that, a new grading increment calculation system was developed. The author called it "Pythagoras grading". For this experiment, specs A and B of T-shirts were selected. Details are given below.

3.2.4.1 Pythagoras grading for pattern pieces of T-shirt sleeve (spec B)

Pattern construction of a T-shirt sleeve can be divided into some geometries that are shown in Figure 21.

Table 5: Diagonal and curve length comparison of pattern pieces of T-shirt body part (spec B) with conventional and automatic grading of BokeCAD

Point of measures	Measurement comparison	Size					Unit
		S	M	L*	XL	XXL	
Sleeve armhole straight	Error after conventional grading	+0.43	+0.21	0.00	−0.21	−0.43	cm
	Length acquired after conventional grading	25.43	26.21	27.00*	27.79	28.57	
	Length required	**25.00**	**26.00**	**27.00***	**28.00**	**29.00**	
	Length acquired after automatic grading	25.00	26.00	27.00*	28.00	29.00	
	Error after automatic grading	0.00	0.00	0.00	0.00	0.00	
Front sleeve curve	Error after conventional grading	+0.51	+0.26	0.00	−0.26	−0.51	
	Length acquired after conventional grading	25.90	26.70	27.50*	28.30	29.10	cm
	Length required	**25.39**	**26.44**	**27.50***	**28.56**	**29.61**	
	Length acquired after automatic grading	25.46	26.48	27.50*	28.52	29.55	
	Error after automatic grading	+0.07	+0.04	0.00	−0.04	−0.06	
Back sleeve curve	Error after conventional grading	+0.51	+0.25	0.00	−0.26	−0.52	cm
	Length acquired after conventional grading	25.85	26.65	27.45*	28.24	29.04	
	Length required	**25.34**	**26.40**	**27.45***	**28.50**	**29.56**	
	Length acquired after automatic grading	25.40	26.42	27.45*	28.47	29.49	
	Error after automatic grading	+0.06	+0.02	0.00	−0.03	−0.07	
*Note: * indicates base size*							

Table 6: Diagonal and curve length comparison of body part (spec A) with conventional and automatic grading of BokeCAD

Point of measures	Measurement comparison	Size					Unit
		S	M	L*	XL	XXL	
Sleeve armhole straight	Error after conventional grading	+0.42	+0.21	0.00	−0.21	−0.42	cm
	Length acquired after conventional grading	25.42	26.21	27.00*	27.79	28.58	
	Length required	**25.00**	**26.00**	**27.00***	**28.00**	**29.00**	
	Length acquired after automatic grading	25.00	26.00	27.00*	28.00	29.00	
	Error after automatic grading	0.00	0.00	0.00	0.00	0.00	
Under sleeve	Error after conventional grading	−0.18	−0.10	0.00	+0.12	+0.25	cm
	Length acquired after conventional grading	13.82	14.40	15.00*	15.62	16.25	
	Length Required	**14.00**	**14.50**	**15.00***	**15.50**	**16.00**	
	Length acquired after automatic grading	14.00	14.50	15.00*	15.50	16.00	
	Error after automatic grading	0.00	0.00	0.00	0.00	0.00	

Point of measures	Measurement comparison	Size					Unit
		S	M	L*	XL	XXL	
Front sleeve curve	Error after conventional grading	+0.50	+0.25	0.00	−0.25	−0.50	cm
	Length acquired after conventional grading	25.84	26.65	27.45*	28.25	29.06	
	Length required	**25.34**	**26.40**	**27.45***	**28.50**	**29.56**	
	Length acquired after automatic grading	25.41	26.43	27.45*	28.47	29.48	
	Error after automatic grading	+0.07	+0.03	0.00	−0.03	−0.08	
Back sleeve curve	Error after conventional grading	+0.50	+0.25	0.00	−0.25	−0.50	cm
	Length acquired after conventional grading	25.75	26.55	27.35*	28.15	28.95	
	Length required	**25.25**	**26.30**	**27.35***	**28.40**	**29.45**	
	Length acquired after automatic grading	25.33	26.34	27.35*	28.37	29.38	
	Error after automatic grading	+0.08	+0.04	0.00	−0.03	−0.07	

*Note: * indicates base size*

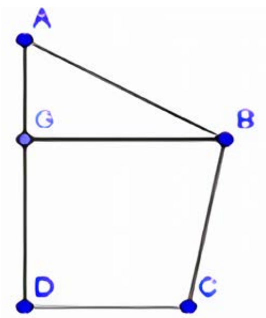

Figure 21: Points to calculate Pythagoras grading for pattern pieces of T-shirt sleeve of spec B

According to Pythagoras law from Δ ABG (cf. Figure 21):

$$AG^2 + GB^2 = AB^2 \quad (13),$$

where AB = sleeve armhole straight and GB = sleeve width.

For L size:

$$AG_L = \sqrt{AB_L{}^2 - GB_L{}^2} = \sqrt{27^2 - 24.5^2} = 11.35 \quad (14),$$

for XL size:

$$AG_{XL} = \sqrt{AB_{XL}{}^2 - GB_{XL}{}^2} = \sqrt{28^2 - 25.25^2} = 12.10 \quad (15).$$

The x-axis value of point A = 0 and the y-axis value of point A = 12.10 – 11.35 = 0.75; the y-axis value of

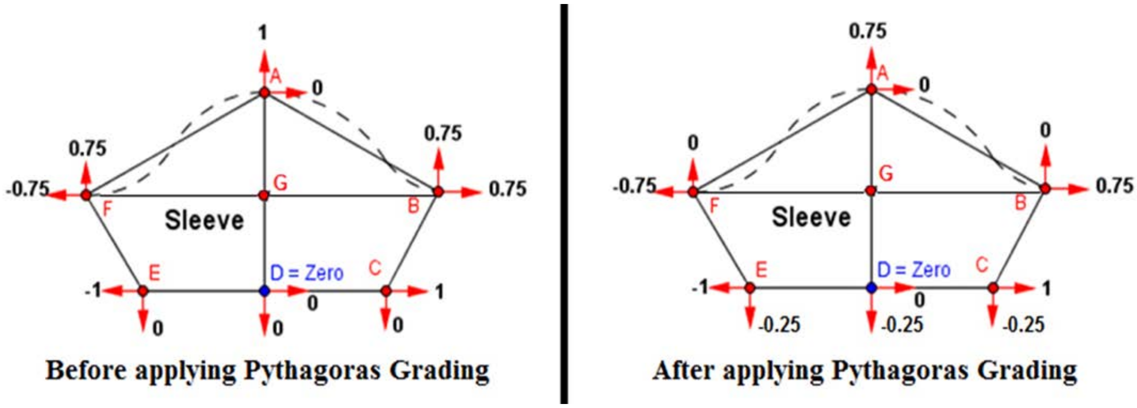

Figure 22: Grading increment of pattern pieces of T-shirt sleeve of spec B before and after Pythagoras grading

point D = (1 – 0.75) = –0.25; and the x-axis value of point D = 0. Therefore, the value of A = (0, 0.75), B = (0.75, 0), C = (1, –0.25), D = (0, –0.25) and G = (0, 0). After applying Pythagoras grading, the grading increment values change, which is shown in Figure 22. The diagonal and curve measurements found after the grading are shown in Table 7.
Based on data in Table 7, it can be said that diagonal and curve grading is up to 0.1 cm error, which is negligible. However, if the under sleeve is given instead of sleeve width, then the calculation is more difficult.

3.2.4.1.1 Pythagoras grading for pattern pieces of T-shirt sleeve (spec A) (method 1)

The pattern construction of a T-shirt sleeve can be divided into some geometries that are shown in Figure 23.

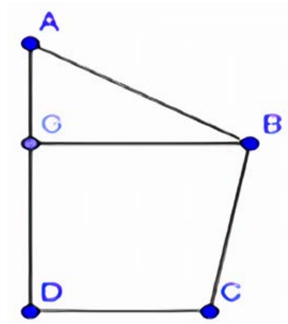

Figure 23: Points to calculate Pythagoras grading for pattern pieces of T-shirt sleeve of spec B (method 1)

After drawing the pattern and then manually measuring the length, the following measurements were found: $AG_L = 9.02$ and $GB_L = 25.45$ (cf. Figure 23). For the grading of sleeve length, the total amount of the grading increment (1 cm) was distributed

Table 7: Diagonal and curve length comparison of sleeve pattern piece (spec B) with conventional and Pythagoras grading

Point of measures	Measurement comparison	Size					Unit
		S	M	L*	XL	XXL	
Sleeve armhole straight	Error before applying Pythagoras law	+0.43	+0.21	0.00	–0.21	–0.43	cm
	Length acquired before applying Pythagoras law	25.43	26.21	27.00*	27.79	28.57	
	Length required	**25.00**	**26.00**	**27.00***	**28.00**	**29.00**	
	Length acquired after applying Pythagoras law	25.02	26.01	27.00*	28.00	29.00	
	Error after applying Pythagoras law	+0.02	+0.01	0.00	0.00	0.00	
Front sleeve curve	Error before applying Pythagoras law	+0.51	+0.26	0.00	–0.26	–0.51	cm
	Length acquired before applying Pythagoras law	25.90	26.70	27.50*	28.30	29.10	
	Length required	**25.39**	**26.44**	**27.50***	**28.56**	**29.61**	
	Length acquired after applying Pythagoras law	25.48	26.49	27.50*	28.52	29.54	
	Error after applying Pythagoras law	+0.09	+0.05	0.00	–0.04	–0.07	
Back sleeve curve	Error before applying Pythagoras law	+0.51	+0.25	0.00	–0.26	–0.52	cm
	Length acquired before applying Pythagoras law	25.85	26.65	27.45*	28.24	29.04	
	Length required	**25.34**	**26.40**	**27.45***	**28.50**	**29.56**	
	Length acquired after applying Pythagoras law	25.44	26.44	27.45*	28.47	29.48	
	Error after applying Pythagoras law	+0.10	+0.04	0.00	–0.03	–0.08	

*Note: * indicates base size*

equally on both sides of the zero-point G; hence, $AG_{XL} = (9.02 + 0.5) = 9.52$.
From ΔAGB (cf. Figure 23), according to Pythagoras law:

$$AG^2 + GB^2 = AB^2 \quad (16),$$

and for XL size:

$$GB_{XL} = \sqrt{28^2 - 9.52^2} = 26.33 \quad (17).$$

The x-axis value of point B = (26.33 – 25.45) = 0.88 and the y-axis value of point B = 0; the value of point A = (0, 0.5), B = (0.88, 0), C = (1, −0.5), D = (0, −0.5) and G = (0, 0).
After applying Pythagoras grading, the grading increment values change, as shown in Figure 24.
After applying Pythagoras grading, the graded measurements changed and are shown in Table 8.

3.2.4.1.2 Grading calculation for pattern pieces of T-shirt sleeve (spec A) (method 2 – two sleeves drawing from same starting point)

The pattern construction of a T-shirt sleeve can be divided into some geometries when overlapping two consecutive sizes (base size and size next to it), which is shown in Figure 25.
From point D (cf. Figure 25), if the pattern of the sleeve is drawn as AD and A2D = sleeve length for L and XL size, DC and DC2 = sleeve opening for L and XL size, AB and A2B2 = armhole straight for L and XL size, and CB and C2B2 = under sleeve for L and XL size, the calculation can be done as value A = (0, 1), D = (0, 0), C = (1, 0) as in the conventional method.
However, for calculating the increment of B point, 2 lines from B and B2 points must be extended to intersect at point P. Now, the measurement can be performed manually to measure the values of BP

Table 8: Diagonal and curve length comparison of pattern pieces of T-shirt body part (spec A – method 1) with conventional and Pythagoras grading

Point of Measures	Measurement comparison	Size					Unit
		S	M	L*	XL	XXL	
Sleeve armhole straight	Error before correction	+0.42	+0.21	0.00	−0.21	−0.42	cm
	Length acquired before correction	25.42	26.21	27.00*	27.79	28.58	
	Length required	**25.00**	**26.00**	**27.00***	**28.00**	**29.00**	
	Length acquired after method 1	25.01	26.00	27.00*	28.00	29.00	
	Error after method 1	+0.01	0.00	0.00	0.00	0.00	
Under sleeve	Error before correction	−0.18	−0.10	0.00	+0.12	+0.25	cm
	Length acquired before correction	13.82	14.40	15.00*	15.62	16.25	
	Length required	**14.00**	**14.50**	**15.00***	**15.50**	**16.00**	
	Length acquired after method 1	14.17	14.58	15.00*	15.43	15.86	
	Error after method 1	+0.17	+0.08	0.00	−0.07	−0.14	
Front sleeve curve	Error before correction	+0.50	+0.25	0.00	−0.25	−0.50	cm
	Length acquired before correction	25.84	26.65	27.45*	28.25	29.06	
	Length required	**25.34**	**26.40**	**27.45***	**28.50**	**29.56**	
	Length acquired after method 1	25.42	26.44	27.45*	28.46	29.48	
	Error after method 1	+0.08	+0.04	0.00	−0.04	−0.08	
Back sleeve curve	Error before correction	+0.50	+0.25	0.00	−0.25	−0.50	cm
	Length acquired before correction	25.75	26.55	27.35*	28.15	28.95	
	Length required	**25.25**	**26.30**	**27.35***	**28.40**	**29.45**	
	Length acquired after method 1	25.33	26.34	27.35*	28.36	29.37	
	Error after method 1	+0.08	+0.04	0.00	−0.04	−0.08	

*Note: * indicates base size*

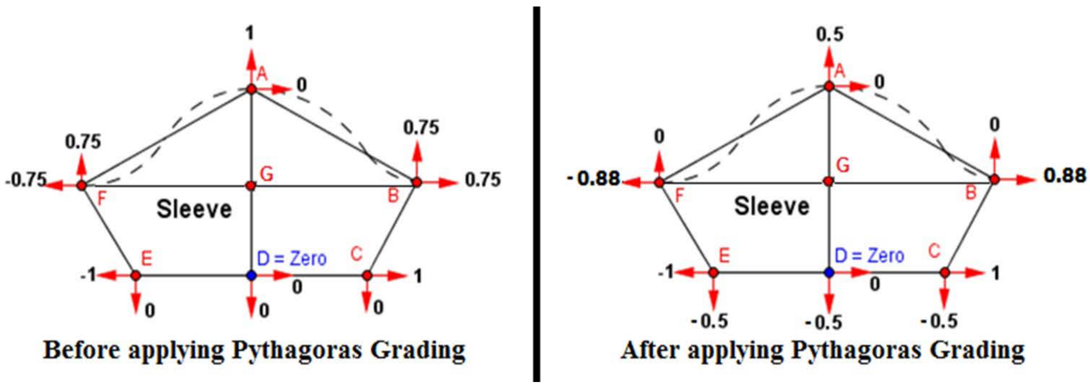

Figure 24: Grading increment of pattern pieces of T-shirt sleeve spec A (method 1) before and after applying Pythagoras grading

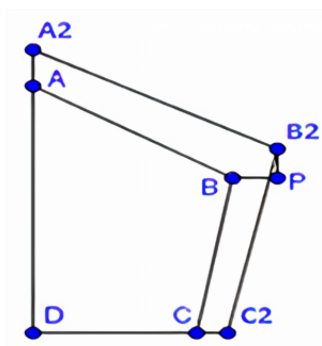

Figure 25: Points to calculate grading increment for the pattern pieces of T-shirt sleeve pattern of spec A (method 2)

and B2P, which are actually the x- and y-axis values of B point. Hence, B = (0.91, 0.57).
After applying method 2, the grading increment values change, which is shown in Figure 26.
The measurements found after the grading can be seen in Table 9.

Regarding data in Table 9, it can be said that there is a minimum deviation from the original measurements, i.e. only up to 0.01 cm error, which is negligible. The values can also be slightly adjusted (increase or decrease as required) to get 100% accurate length. If sleeve width is given instead of under-sleeve, then it is very easier to calculate the grading increments.

4 Recommendation for presence of diagonal and curve measurements

4.1 Recommendation for problem 1 – presence of diagonal measurements

Diagonal measurements should be avoided as much as possible in the spec sheet since they cause grading deficiency. If the diagonal measurement exists in a spec sheet, then the measurement checking and manual manipulation in grading increment should be conducted to rectify the measurements. It can be

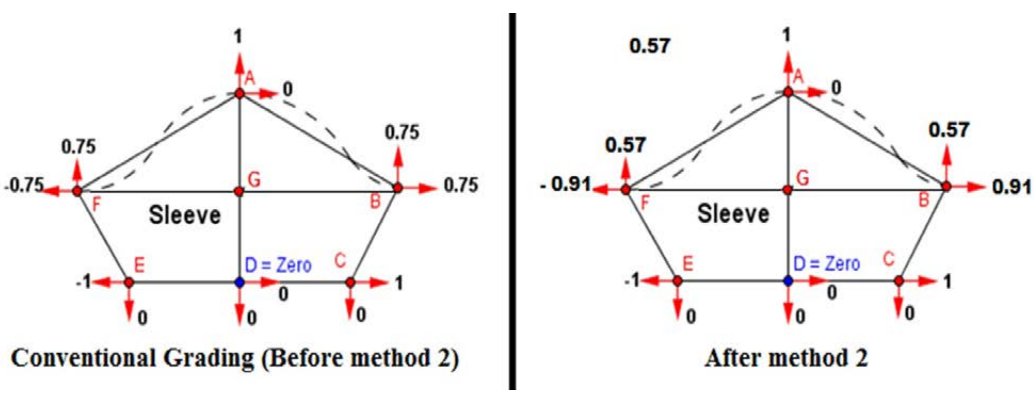

Figure 26: Grading increment of pattern pieces of T-shirt sleeve spec A before and after applying method 2

Table 9: Diagonal and curve length comparison of pattern pieces of T-shirt body part (spec A – method 2)

Point of measures	Measurement comparison	Size					Unit
		S	M	L*	XL	XXL	
Sleeve armhole straight	Error before correction	+0.42	+0.21	0.00	–0.21	–0.42	cm
	Length acquired before correction	25.42	26.21	27.00*	27.79	28.58	
	Length required	**25.00**	**26.00**	**27.00***	**28.00**	**29.00**	
	Length acquired after method 2	25.00	26.00	27.00*	28.00	29.00	
	Error after method 2	0.00	0.00	0.00	0.00	0.00	
Under sleeve	Error before correction	–0.18	–0.10	0.00	+0.12	+0.25	cm
	Length acquired before correction	13.82	14.40	15.00*	15.62	16.25	
	Length required	14.00	14.50	15.00*	15.50	16.00	
	Length acquired after method 2	14.02	14.5	15.00*	15.50	16.01	
	Error after method 2	+0.02	0.00	0.00	0.00	+0.01	
Front sleeve curve	Error before correction	+0.50	+0.25	0.00	–0.25	–0.50	cm
	Length acquired before correction	25.84	26.65	27.45*	28.25	29.06	
	Length required	**25.34**	**26.40**	**27.45***	**28.50**	**29.56**	
	Length acquired after method 2	25.41	26.43	27.45*	28.47	29.48	
	Error after method 2	+0.08	+0.03	0.00	–0.03	–0.08	
Back sleeve curve	Error before correction	+0.50	+0.25	0.00	–0.25	–0.50	cm
	Length acquired before correction	25.75	26.55	27.35*	28.15	28.95	
	Length required	**25.25**	**26.30**	**27.35***	**28.40**	**29.45**	
	Length acquired after method 1	25.32	26.34	27.35*	28.36	29.38	
	Error after method 1	+0.07	+0.04	0.00	–0.04	–0.07	

*Note: * indicates base size*

done in any garment CAD. However, if Optitex or TukaCAD is available, then the "measure and segment editor" function can be used to minimise the diagonal line grading error. If BokeCAD is available, then "automatic grading" can be used instead of "conventional grading" as both methods are available in BokeCAD. Even if Optitex or TukaCAD or BokeCAD is not available, or we are not familiar with the particular function to rectify grading, then Pythagoras grading can be used to minimise inclined line grading errors.

4.2 Recommendation for problem 2 – presence of curve measurements

Measurement checking and manual manipulation for the grading increment should be performed until the required curve lengths are achieved. If Optitex or TukaCAD is available, use the "measure and segment editor tool" to rectify the curve line grading. If Boke CAD is available, then there is no need to rectify the grading since it has an automatic grading system for higher precision grading. If that software is not available or we are not familiar with the described tools, then use the Pythagoras grading system developed by the author.

5 Conclusion

During the production, pattern pieces must be increased or decreased geometrically to create a complete range of sizes to produce clothing that fits various body types and sizes. Size specifications vary slightly from manufacturer to manufacturer and each company determines its own grade specifications for each size. Grading is still the most effective method to create multiple sizes from base size according to the size chart for the clothing production (even though the grading calculation can be slightly tricky and complex), since it is less time consuming and it supports downstream operations such as marker making and cutting. Computerised grading with different 2D and 3D CAD systems are not free from limitations even though they provide the most efficient method of pattern making, grading and marker making. There are different techniques and tools available in different garment CADs to rectify grading errors. However, the tools and techniques provided by different CADs are different from one another and different techniques have different levels of complexity and accuracy. The findings and recommendations will help the pattern grader to minimise and rectify grading deficiencies. If it is successfully implemented, it will not only reduce size-set sample approval time but also develop products that fit well to the wearer's body.

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