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Automated Apparel Processing

Computer Simulation of Fabric Deformation for the Design of Equipment

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Introduction

Apparel manufacturing processes are a part of a traditionally highly skilled, labour-intensive industry. The international market is extremely competitive, owing to much lower labour wages. In order to maintain a competitive advantage in the global market, selected apparel assembly operations can be automated. A major focus of apparel automation has been placed on materials handling, because it accounts for 80 per cent of the time needed to manufacture apparel[1]. One of the major limitations of automated equipment for apparel manufacturing is designing a machine which has the flexibility to handle a variety of fabric types and sizes. In order to design equipment to be used for apparel automation, it is necessary to have the ability to predict the behaviour of fabric parts as they are in contact with the machines. It is important to understand fabric bending behaviour, so that these predictions can be made.

In order to design manufacturing systems for apparel automation, it is necessary to have a means of simulating fabric behaviour. The use of simulations allows us to optimize the design of a machine without physically having to change parameters on the machine, thus reducing time and costs. One very important property where simulation would be useful is the bending behaviour of fabric during a process. A computer model has been developed by Dr J.W. Eischen and T.W. McDevitt at North Carolina State University which simulates the behaviour of fabric parts during apparel manufacturing[2]. The model is based on large deflection beam theory and the finite element method to characterize a fabric strip under given loads or displacements. The model will be evaluated in this article and will be compared with experimental research. The design of a fabric feeding device will be used to illustrate how the computer simulation method can be applied.

Computer Model

The computer program which was used incorporated numerical methods to arrive at solutions owing to the difficulty of determining “closed form” solutions. This difficulty arises owing to the limpness of fabrics which are

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subjected to large deflections and rotations. The model uses a practical method of characterizing the fabric strip, whereby the strip is assumed as an elastic continuum. The model is designed for large displacements and rotations of the fabric strip in two dimensions, allowing stretching and bending of the fabric. The behaviour of the fabric is determined by equations derived from differential equilibrium equations. Using a finite element method to discretize the fabric strip, a final set of equations was obtained to comprise a non-linear program. The program can be used to simulate the behaviour of a fabric strip under certain conditions.

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Certain fabric properties are required for the model

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The necessary inputs of the program are: the initial position of the strip; relevant material properties; boundary conditions; and loading conditions. The fabric strip is divided into a number of segments defined by nodal points, as shown in Figure 1. The co-ordinates of these nodal points are specified by the user and entered into the input file. Certain fabric properties are required for the model: fabric thickness, bending rigidity, and the weight per unit area. A set of boundary conditions, based on the support configuration of the fabric element, must be included in the input data file. External loads must also be defined in the input data, and can exist in the following forms: the weight of the fabric itself, assigned forces at any point along the fabric strip, or assigned displacements along the fabric strip. The loads are applied in increments and at time intervals specified by the user. One of the constraints of this model is that it has not been made to accommodate dynamic forces, such as inertial and aerodynamic forces. The model is designed to account for a contact surface for the fabric ply. This surface is also divided into a series of connected nodes defined by co-ordinates provided by the user, as in the case of the fabric part. One limitation of this model is that the contact surface is assumed to be frictionless. An additional constraint of the model is that it considers only the behaviour of one fabric ply on a rigid surface, and cannot consider multiple plies of fabric.

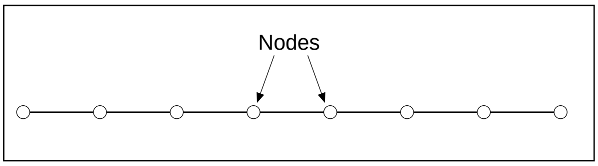

Figure 1.
Nodal Segments

This model was used to simulate the bending behaviour of four woven fabrics, of which the necessary properties of the model are shown in Table I. Owing to the fact that most woven fabrics possess different bending properties in the warp and weft directions, the fabrics were tested in both directions. Therefore, the results were analysed as if there were eight fabrics tested.

In addition to simulating the behaviour of eight fabrics, three contact surfaces were tested with the model, representing the shape of the contact surface of a fabric feeding device, called the bottom feeder. This system picks plies of fabric, one at a time, from the bottom of a stack of fabric parts. Each surface represented in the simulations consisted of a long, flat, horizontal section which was concluded with a curved semicircular section, as shown in Figure 2. The curved portion of the surfaces represents a picking roller in the bottom feeder, which is located beneath the stack of fabric parts. The surfaces were varied by using end surface diameters of 6.033cm (2.375in), 10.16cm (4in), and 15.24cm (6in).

Each sample simulated was 30cm long and 1cm wide, and was divided into 60 linear segments, defined by 61 nodal points, for the finite element analysis of the fabric piece. Initially, the fabric strip was positioned along the fiat portion of the contact surface. The rigid contact surface, which was assumed to be frictionless, was broken down into 37 linear segments, defined by 38 nodal points. The first segment characterizes the flat portion of the surface, and the remaining segments define the geometry of the curved component.

Fabric	Bending rigidity (gm – cm^2/cm)	Thickness (cm)	Weight (gmf/cm)
1	0.864	0.0512	0.0244
2	0.928	0.0512	0.0244
3	1.111	0.0471	0.0236
4	2.294	0.0471	0.0236
5	0.336	0.0588	0.0267
6	0.514	0.0588	0.0267
7	0.143	0.0322	0.0145
8	0.178	0.0332	0.0145

Table I.
Fabric Properties

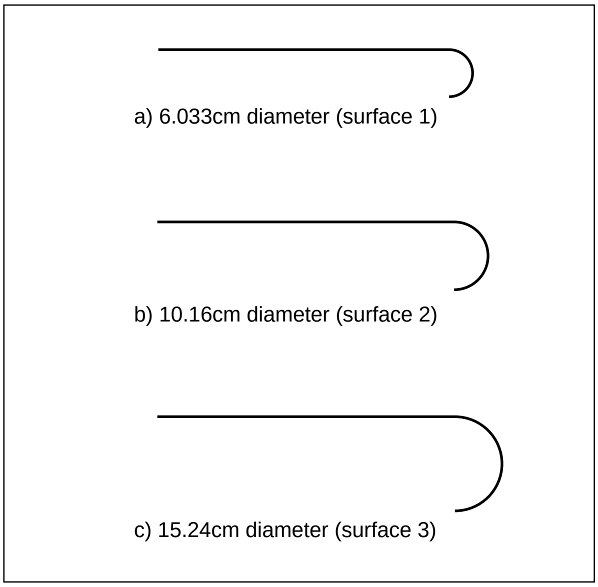

Figure 2.
Fabric Contact Surfaces

A similar representation is shown in Figure 3, where only 12 segments are used to define the curved component. The simulations were carried out by applying two loads to the fabric strip: the weight of the fabric itself and a force applied to push the fabric along the surface. For some simulations to converge, it was necessary to increase the number of time steps of the load functions and, initially to apply the loads gently.

The results of the simulations are graphically presented as the stepwise displacement of the fabric (*s*) versus the horizontal (δ_h) or vertical displacement (δ_v). Figure 4 shows the reference used to obtain the horizontal and vertical displacements of the tip of the fabric sample as it is moved along the surface. The curves of the graph are defined by co-ordinates produced by the computer model, and are given in increments of 2cm from 0 to 20cm of fabric displacement.

The results of the simulation of fabric 1 being moved along surface 1 is shown in Figure 5, and along surface 3 in Figure 6. The horizontal displacement levels out after an inflection point,

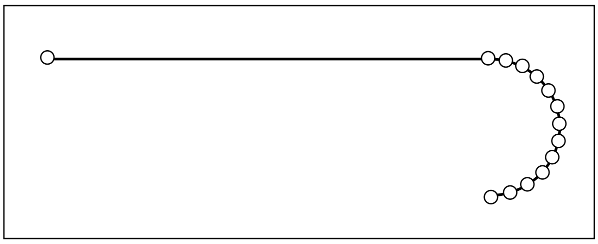

Figure 3.
Contact Surface Model

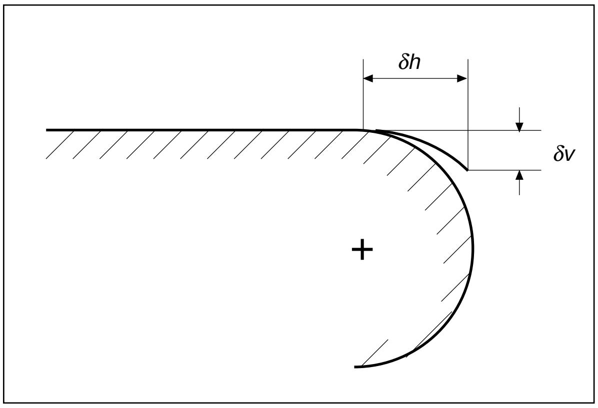

Figure 4.
Horizontal and Vertical Displacements of Fabric Edge

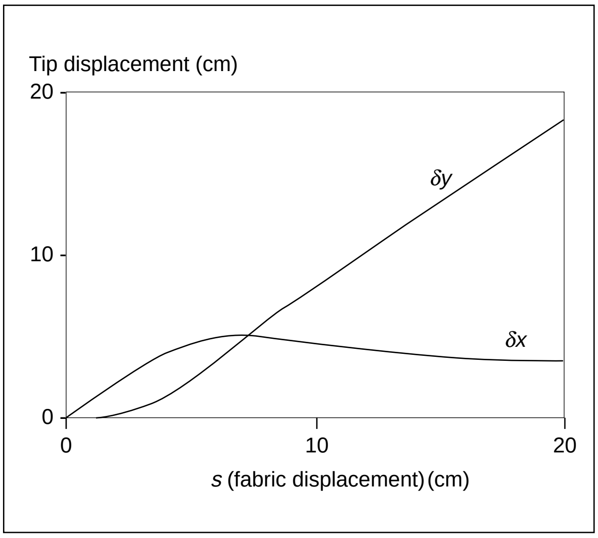

Figure 5.
Simulated Horizontal and Vertical Tip Displacements (Fabric 1, Surface 1)

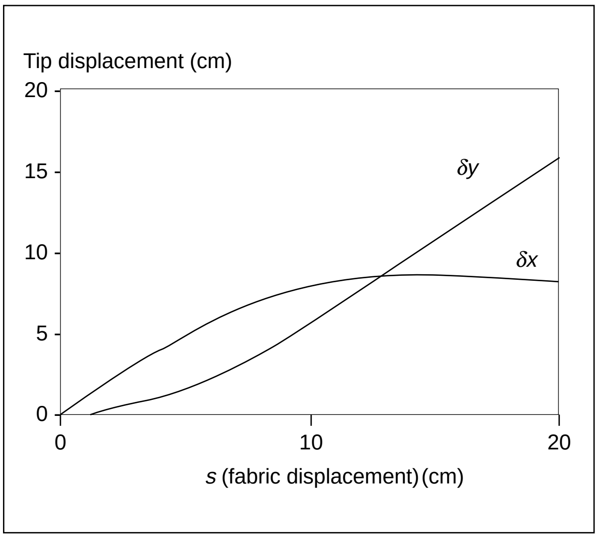

Figure 6.
Simulated Horizontal and Vertical Tip Displacements (Fabric 1, Surface 3)

and the vertical displacement increases linearly after an inflection point, as expected. The results of the simulations using the other fabrics and surfaces were found to exhibit the same general trends.

When comparing the graphs based upon bending rigidity, the curves of the fabrics with lower bending rigidities have inflections occurring sooner than the fabrics of higher bending rigidities. This result is expected, because stiff fabrics have a larger bending curvature which must be overcome before the fabric will begin to drape vertically over the curved surface (Figure 7). It is also observed that when simulations were run using a surface with a larger-diameter curved end, the displacement curves exhibited later inflections than those using a smaller-diameter curved end surface. In other words, the greater the curvature diameter of the end surface, the greater the bending curvature of the fabric.

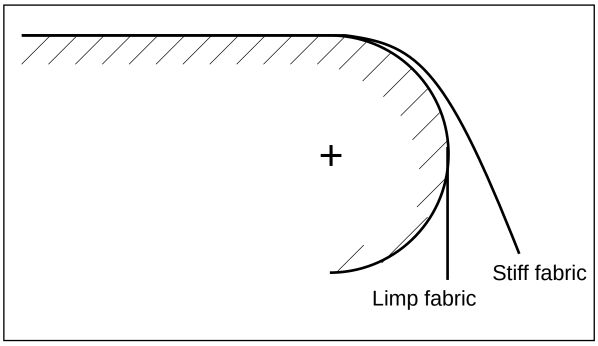

Figure 7.
Bending Curvature of Limp vs Stiff Fabric

The analysis of the results of the finite element computer model suggests that it could be valid for simulating the bending behaviour of a range of woven fabrics. In order to make use of the simulated results, the computer model must be validated by experimentation. Experiments were carried out under similar boundary conditions that were defined for the finite element model simulations. The data obtained from these experiments were then compared to the data produced by the model simulations, and conclusions were made based on these comparisons.

Experimental Validation

In order to perform testing, the experiments were set up to resemble the conditions of the computer model simulations. A typical setup of the components used for testing and for recording results is shown in Figure 8. Three surfaces were made from 0.3175cm (0.125in) aluminium sheets which were each rolled on one end to form a curved-end surface with a diameter of 6.033cm (2.375in), 10.16cm (4in), or 15.24cm (6in), as shown in Figure 2. Each surface was affixed by an adhesive to a plywood board for stability and then placed on a box during testing. Other equipment used for the experiments was a Javelin television video camera, a Tokina zoom lens, a Matrox

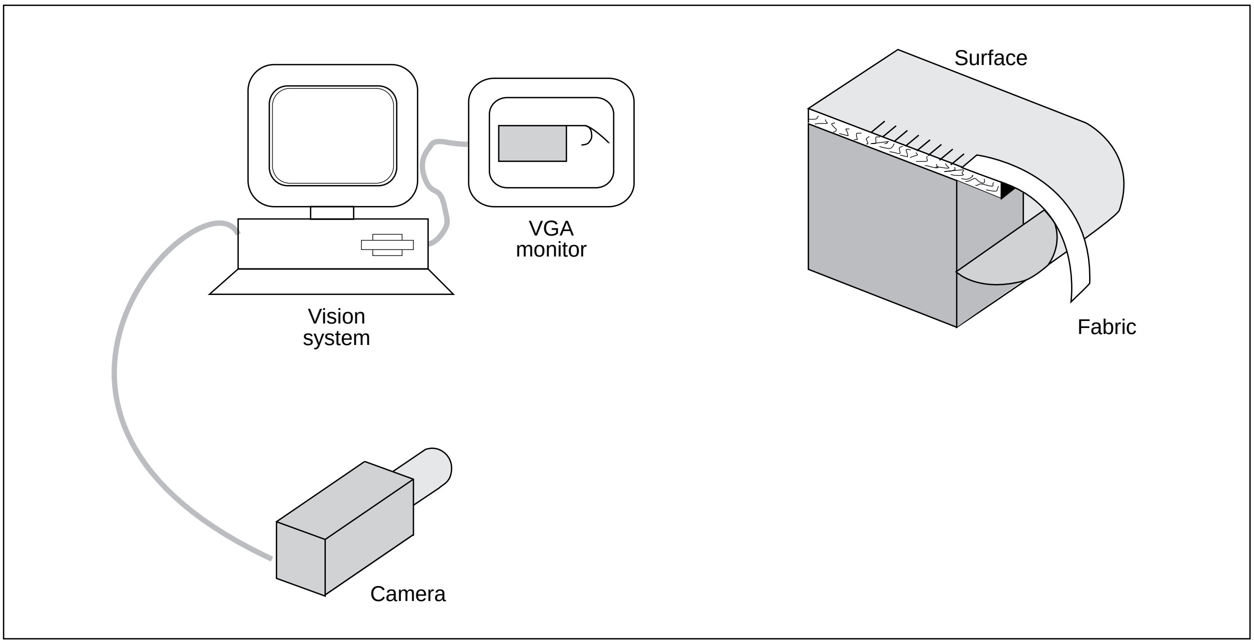

Figure 8.
Experimental Setup

vision board, and a standard PC. In addition to the apparatus used, a computer program, written in C language, was used to determine the data. An image was captured and corresponding pixel values were stored on the vision board. The program analysed these values in order to determine pixel co-ordinates of the fabric edge, which were stored in output files.

Before the experiments could be performed, the vision system setup had to be calibrated. An image in the vision board was stored as intensities of pixels contained in a rectangular area measuring 512 horizontal pixels and 480 vertical pixels. Intensities were measured as values ranging from 0 to 256, where 0 is black and 256 is white. A threshold pixel value was determined in order for the experimental values to be binarized as black or white. The program analysed pixel values row by row, starting from the top right-hand corner of the image, in order to determine the location of the edge of the fabric, defined by black pixel values. The co-ordinates of the first black pixel value in each row were saved to an output file. In addition to determining a threshold value, horizontal and vertical scales had to be calculated in order to convert from pixels to centimetres. Images of objects of known dimensions were taken, and 6 pixels were found to equal 1cm both in the horizontal and the vertical directions.

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The horizontal and vertical displacements were plotted on one graph

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Three samples of each fabric described in the previous section were cut and tested. Each fabric sample was originally positioned on the surface with its leading edge resting on the tangent point of the curved surface, in the same way as simulated in the model. The camera and attached zoom lens were placed about 10 metres from the fabric sample, which was positioned on the surface, and was focused in order to capture the image. The vision board then retrieved and stored the captured image from the camera in the form of pixel values, from which the appropriate data were extracted and sent to output files. The sample was then pushed 2cm towards the curved end of the surface in order to capture the next image. The fabric continued to be pushed in increments of 2cm over the curved surface, recording images of each step, until it had been displaced 20cm from its original position. The recorded images were stored for analysis.

Several steps had to be taken to transform the data for comparison with the model simulations. The data consisted of pixel co-ordinates corresponding to the edge of the fabric sample. The only data needed for this research were the co-ordinates of the tip of the fabric sample. Therefore, the appropriate co-ordinates had to be determined from the entire set. Each data set was analysed, and the pertinent co-ordinates were obtained.

The data values were further manipulated by subtracting out co-ordinate values of the reference point of the surface (Figure 4). The final transformation of the data was done by scaling the pixel values to obtain horizontal and vertical tip displacements in units of centimetres.

As seen in Figure 9, the set of data points of each replicate coincided or fell very close together, therefore showing the low variation among the experimental results. The standard deviations among each set of three points were calculated for this representative case, and were found to be about 1mm (Table II). The plotted results of experimental testing exhibited take characteristics similar to those of the computer simulations, as discussed previously.

When the experimental data had been transformed into a format compatible with the theoretical results of the finite element model, observational and statistical analyses could be made. The horizontal and vertical displacements of the tip of the fabric sample, as determined by model simulations and experimental testing, were plotted on one graph for each fabric-surface

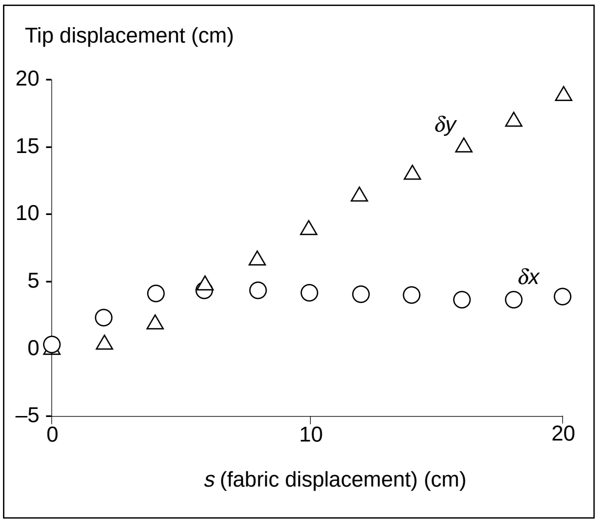

Figure 9.
Experimental Horizontal and Vertical Tip Displacements (Fabric 7, Surface 3)

Fabric displacement step (cm)	Standard deviation (cm)	
	x-displacement	*y*-displacement
2	0.0981	0.0924
4	0.0981	0.0058
6	0.0000	0.0981
8	0.0924	0.0058
10	0.0981	0.0058
12	0.0981	0.0000
14	0.0981	0.0058
16	0.0924	0.0058
18	0.0924	0.0954
20	0.1905	0.0058

Table II.
Standard Deviation among Experimental Data Points

combination. Figure 10 shows one of these graphs, where the curves represent the simulated results and the points refer to experimental data.

In general, the graphs suggested strong relationships between theoretical and experimental data, as seen in Figure 10.

Results

Statistical analysis of the simulated and experimental data was necessary to evaluate their relationship further. A Pearson's product-moment coefficient of determination was determined for the paired data of the simulated results and the average experimental results for each case, and is shown in Table III. Most of the values in the table suggest that there exists a high correlation between the simulated results of the computer model and experimental results. One exception which is not high enough to suggest that the computer model was capable of explaining the variation of tip deflection of fabric as it is pushed over a curved surface is the case of fabric 6 and surface 1. This exception occurs because this case involves the smallest diameter surface and a very limp fabric.

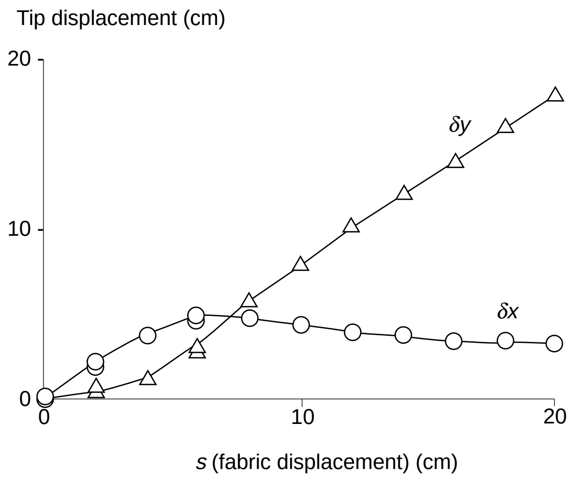

Figure 10.
Combined Horizontal and Vertical Displacements (Fabric 1, Surface 1)

There were several sources of error for the collection of experimental data, as well as the computer model simulations. One possible source of error was the operator, because the fabric sample was manually moved for each step.

Other experimental errors were owing to camera resolution and the condition of the fabric samples. Some fabrics were deformed owing to previous folding or position on the roll of fabric. Owing to these factors, some fabric samples showed a curvature, when the computer model predicted none. Therefore, there was a decrease in horizontal deflection of the experimental data while that of

	Surface 1		Surface 2		Surface 3	
Fabric	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
1	0.991	0.999	0.997	0.999	0.998	0.999
2	0.973	0.998	0.988	0.999	0.994	0.999
3	0.860	0.998	0.994	0.998	0.997	0.994
4	0.893	0.998	0.928	0.995	0.958	0.978
5	0.627	0.997	0.801	0.994	0.957	0.997
6	0.000	0.898	0.915	0.996	0.998	0.998
7	0.964	0.998	0.976	0.998	0.993	0.998
8	0.662	0.985	0.961	0.998	0.999	0.999

Table III.
Pearson's Product-moment Coefficients of Determination (R^2)

the simulation remained constant. Even though these are common situations in real uses of fabric, the computer model did not account for these circumstances. An additional source of error was the values of bending rigidity of the fabrics used, as determined by FAST testing. The FAST system determines one value for bending rigidity and assumes that it is a linear property, when it has been shown to be a non-linear property.

Conclusions

After evaluation of the finite element computer model through experimental testing, it was found

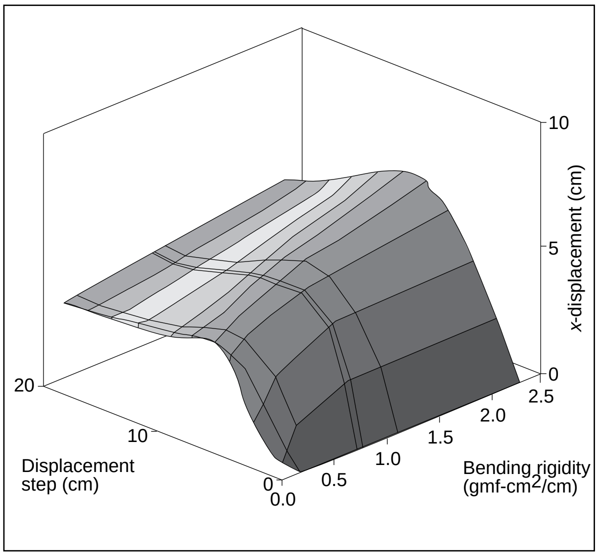

Figure 11.
Horizontal Displacement – 6.033cm Diameter

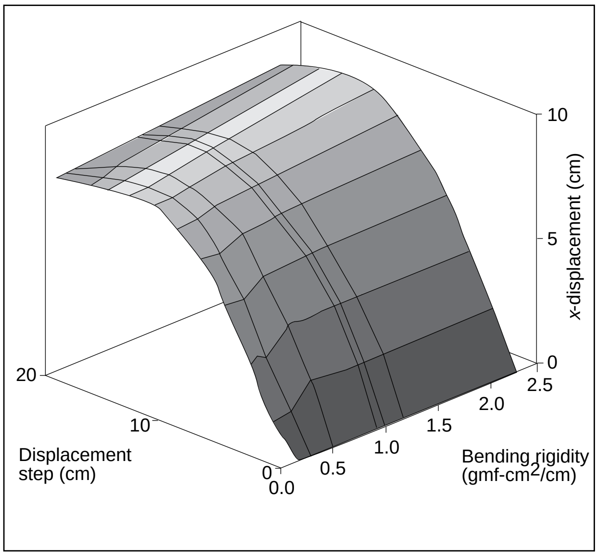

Figure 12.
Horizontal Displacement – 15.24cm Diameter

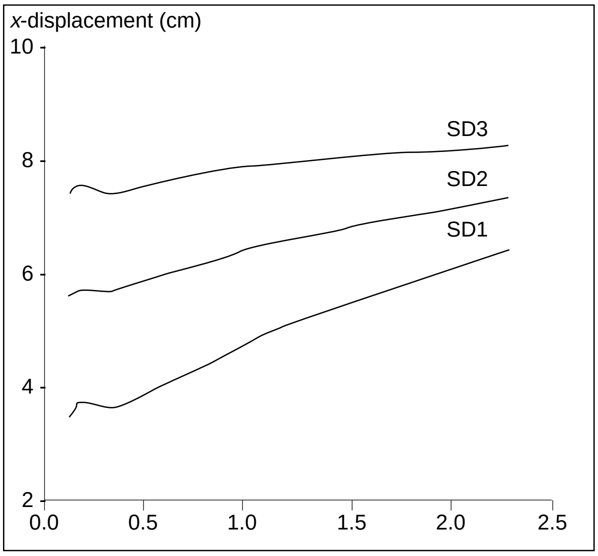

Figure 13.
Horizontal Displacement – s = 10cm

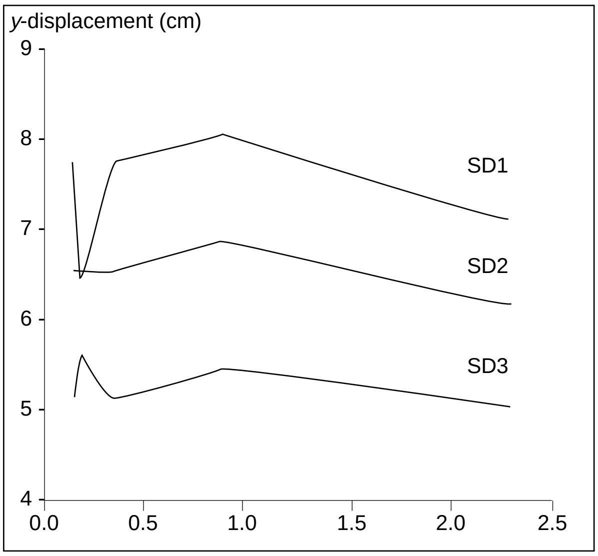

Figure 14.
Vertical Displacement – s = 10cm

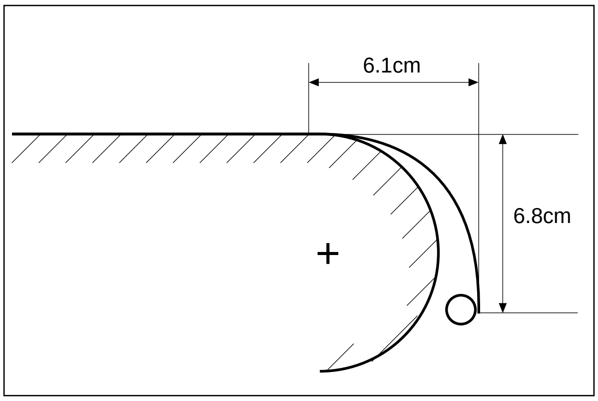

Figure 15.
Example of Gap Setting

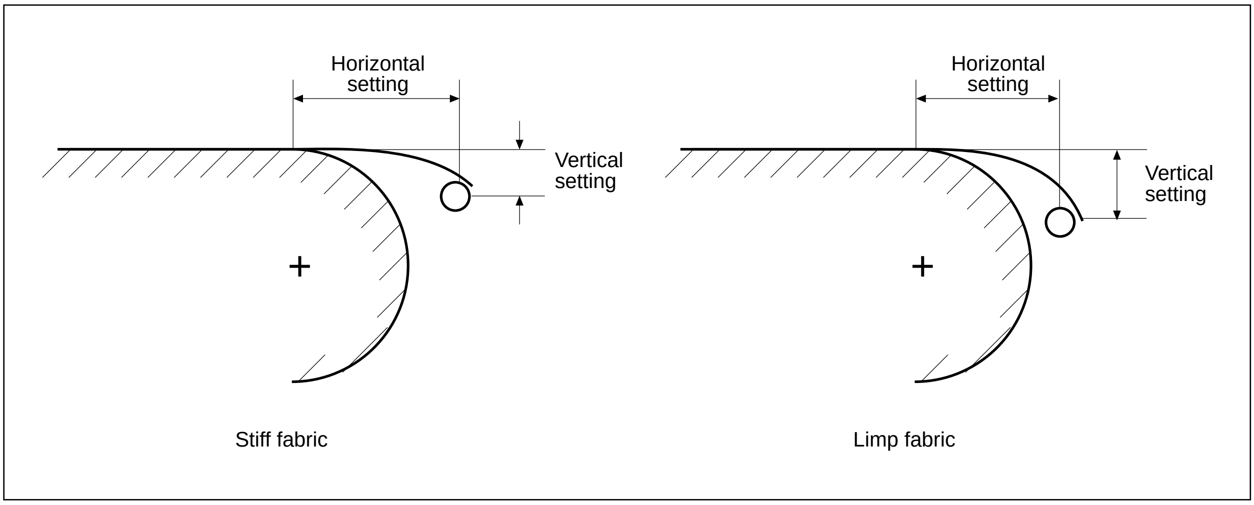

Figure 16.
Gap Adjustment Bar Position for Stiff and Limp Fabrics

that the model was a valid approximation of the bending behaviour of fabric over a curved surface. In addition to the evaluation of the computer model performed here, further testing needs to be done, where different boundary conditions would be used. Further improvements for the computer model would be to develop the model to accommodate dynamic forces, as are present in fabric handling. The results obtained from the simulations can be used to choose an optimum diameter of the picking roller in the bottom feeder. If the range of location of the gap adjustment bar is known, it can be determined whether or not a fabric ply will successfully pass above the bar. Therefore, the diameter of the picking roller depends on the range of movement of the gap adjustment bar. The model should also be tested for the ability of its results to be implemented in apparel manufacturing processes.

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Increase in diameter causes an increase in horizontal displacement

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Statistical analysis was performed to determine the factors which produced significant effects on the horizontal and vertical displacements of the fabric tip. The factors tested were surface diameter (SD), fabric thickness (TH), fabric bending rigidity (BR), and the fabric displacement step (S). The dam points of the computer model output were analysed using SAS, which showed surface diameter and bending rigidity to have significant effects on the horizontal displacement of the fabric tip. The displacement step also had a significant effect both on horizontal and on vertical displacement, but this result was obviously anticipated.

Figures 11-12 show the effects of fabric step displacement and bending rigidity on horizontal tip displacement of the fabric strips for each surface diameter. A comparison of the graphs shows that an increase in diameter causes an increase in horizontal displacement. In other words, the fabric has less curvature on a larger diameter surface. This effect was also shown for the vertical displacement, where it decreases with an increase in surface diameter. The graphs also demonstrated that an increase in bending rigidity was found to increase the horizontal displacement; however, there was no significant effect on vertical displacement. Therefore, a stiffer fabric has a larger horizontal displacement as it is pushed over a contact surface. It is also important to notice the peaks of the surface plots, which indicate the displacement step where a fabric tip drops and continues to fall straight vertically. As surface diameter increased the peak occurred at a higher displacement step. A larger surface diameter would be more desirable because the fabric tip positions would be very similar for a wider range of bending rigidities and the fabric plies would be more likely to pass above the gap adjustment bar.

Using this information, an appropriate diameter and gap setting can be chosen, based on how far a fabric strip will be pushed at the point it is picked from the bottom of the stack. In order for a fabric to be successfully picked from a stack, the gap must be properly set to allow passage of the bottom ply only. Therefore, the second ply must remain above the gap adjustment bar during operation of the machine. For example, suppose that the second ply of a fabric, which has a bending rigidity of 0.750 gmf-cm^2/cm, has been displaced 10cm from a machine cylinder with a diameter of 10.16cm. Using these values and the graphs in Figures 13 and 14, the horizontal and vertical displacements of the fabric tip would be 6.1cm and 6.8cm, respectively. Therefore, the horizontal and vertical settings of the gap adjustment bar would be set as shown in Figure 15, where the fabric tip lies above the bar. These settings are approximate, but the vertical adjustment should be set no higher and the horizontal adjustment no larger than the estimated settings so that the ply will pass over the bar. Limp fabrics require a smaller horizontal and a lower vertical gap setting than stiff fabrics (Figure 16).

If the gap setting adjustment is not capable of accommodating a specified range of bending rigidities, the surface diameter of the picking cylinder can be changed. Choosing a surface diameter depends on the allowable adjustments of the gap setting, the bending rigidities, and fabric displacement. As can be seen in Figures 13 and 14, the largest surface diameter causes the horizontal and vertical displacements to have the least variation across a range of bending rigidities. Therefore it would be advantageous to use as large a surface diameter as possible, in order to accommodate a wider range of bending rigidities. The size of the cylinder diameter would also be governed by the ability of the remaining plies of the stack to stay above the gap adjustment bar.

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