Design and research on the posture-adjustable mannequin for chest-up and hunchbacked posture

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GUODONG XU
YUJIA REN
YU CHEN

ABSTRACT – REZUMAT

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The development of garment personalization has put forward diverse requirements for mannequins. In this paper, we present a garment mannequin that can continuously alter the body posture in response to changes in human body posture in the chest and back regions. This research is founded on an analysis of the patterns and ranges of movement in the mannequin's chest and hunchbacked motions. We segmented the mannequin into six modules: neck, front chest, back, left and right shoulders, and waist and abdomen. By employing stepper motors, we independently drive the front chest, back, and left and right shoulders to achieve the simulation and continuous adjustment of the mannequin's body posture for chest and hunchbacked positions. The comparison of the 3D scans shows that the mannequin fits well in several cross-sections with the corresponding body variations of real people, and the results of the real shirt also show that the shirt made based on the simulated hunchbacked body mannequin is significantly better than the standard shirt in terms of comfort and aesthetics for a person with a hunchbacked body posture. The body posture adjustable mannequin can replace multiple static mannequins, which can provide strong support for the business model of personalized clothing customization. Compared with the existing dynamic mannequin, it has the advantages of high relevance, simple structure and low production cost.

Keywords: *adjustable mannequin, garment personalization, hunchbacked posture, chest-up posture, garment customization, 3D scanning, electromechanical integration technology*

Proiectare și studiu asupra manechinului cu postură ajustabilă pentru postura cu spatele drept şi postura cu spatele încovoiat

Dezvoltarea personalizării articolelor de îmbrăcăminte a impus diverse cerințe pentru manechine. În acest studiu, prezentăm un manechin pentru îmbrăcăminte care îşi poate modifica continuu postura ca răspuns la schimbările în postura corpului uman în regiunile pieptului și spatelui. Această cercetare se bazează pe o analiză a tiparelor și intervalelor de mișcare a pieptului manechinului și a mişcărilor cu spatele încovoiat. Am segmentat manechinul în șase module: gât, piept, spate, umărul stâng și umărul drept, talie și abdomen. Prin folosirea motoarelor pas cu pas, am acţionat în mod independent pieptul, spatele, umărul stâng și umărul drept pentru a realiza simularea și ajustarea continuă a posturii corpului manechinului pentru postura cu spatele drept şi postura cu spatele încovoiat. Comparația scanărilor 3D arată că manechinul se potrivește bine în mai multe secțiuni transversale cu variațiile corespunzătoare ale corpului omenesc real, iar rezultatele unei cămăşi reale realizate pe baza manechinului cu spatele încovoiat simulat sunt semnificativ îmbunătățite decât cele ale unei cămăşi standard în ceea ce privește confortul și estetica pentru o persoană cu o postură corporală cu spatele încovoiat. Manechinul cu postura corpului ajustabilă poate înlocui mai multe manechine statice şi poate oferi un sprijin real pentru modelul de afaceri în ceea ce priveşte îmbrăcămintea personalizată. În comparație cu manechinul dinamic existent, are avantajele unei relevanțe ridicate, structură simplă și costuri de producție reduse.

Cuvinte-cheie*: manechin ajustabil, personalizarea articolelor de îmbrăcăminte, postură cu spatele încovoiat, postura cu spatele drept, scanare 3D, tehnologie de integrare electromecanică*

INTRODUCTION

The issue of garment fit permeates garment design and sales [1], and during the design process, designers and pattern makers need to accurately assess the fit of garments to optimize the designed garment products [2]. In apparel retail, consumers' primary concern is garment fit. Irrespective of the clothing's aesthetic appeal, a mismatch in clothing size will deter consumers from making a purchase. Clothing fit remains the principal factor influencing customers' purchase choices [3–7].

Garment fit has emerged as a pivotal measure for assessing garments [4], influenced by a multitude of factors, with body size [5] being a significant criterion. However, people often have habitual chest-up and hunchbacked posture changes, making standardized clothing difficult to fit, and this can not be resolved through the refinement of the clothing size. Research has demonstrated that over 50% of consumers express dissatisfaction with clothing fit [3].

Consequently, the difference in body shape [8] has emerged as a pivotal element for clothing personalization [9].

Mannequins are foundational tools in garment production and fit assessment [10–13], and they serve a pivotal function in personalization. However, existing commercial mannequins are mainly static mannequins with little consideration of body changes, which has led to a dramatic increase in the number of mannequins, not only increasing investment costs but also taking up a lot of space. A common method currently used is pattern correction for standard-size garments [10–12], however, this method still falls short in effectiveness when compared to cutting directly using the corresponding posture garment mannequin. Therefore, adjustable mannequins have been widely studied as an effective method to solve this problem.

About the alteration of the body shape and posture of the mannequin, early methods of augmentation and correction of the standard mannequin were used to obtain the body surface morphology of the mannequin with a chest-up [14–16], a convex belly and a hunchbacked back [17] by filling specific areas with materials such as cotton cores and elastomeric cloth [15]. 3D printing technology has further refined this approach, and the printed padding for the chest, waist, and hip areas can better fit the body's curves [18]. However, this method still has shortcomings such as complicated operation, long time consumption, high cost, and difficulty in achieving concavity, especially because it can cause changes in body shape while the mannequin is changing. Therefore, it is especially important to manufacture adjustable mannequins that can fit the changes in human body posture [19].

A patent by Liu et al. [20] proposed an adjustable mannequin, which cut the torso of the mannequin into seven segments horizontally and achieved continuous changes in the body shape of the mannequin by changing the circumference of each segment. Abels et al. [21] designed a deformable mannequin model for cutting applications, comparing the shape of the human model with the actual human body using the Iterative Closest Point algorithm, and determining the degree of similarity between the human surface model and the actual human body using a defined similarity metric which can assist in exploring improvements to mannequin models. Zhang et al. [22] proposed a microcontroller-controlled fitting robot that deforms the shoulder width, bust and waist circumference of a mannequin through a stepper motor drive system consisting of a guide rail and a sliding table [23]. Weng [24] designed a "skeletal-muscle-skin" multi-layered fitting robot that could simulate shoulder-holding movements by adjusting the position of the shoulder peak point relative to the lateral neck point. However, these mannequins are still not perfect in the simulation of body posture, and it is difficult to simulate shoulder retraction with a chest-up and hunchbacked back. Chan et al. [21] invented an intelligent adjustable mannequin, which could change the body size and structure of the mannequin by driving the movement of the adjustment plate through an internal detector and gear structure. However, the model could only achieve the adjustment of neck circumference, chest circumference, waist circumference, and hip circumference, and could not fit the hunchbacked body shape well.

Guo et al. [23] produced a female mannequin that can change body shape and posture. They have subdivided the mannequin into 29 modules and have driven and controlled each module with up to 21 stepper motors to achieve a continuous change of 10 main parameters of the human body shape and posture. The double-layered panels made of soft materials can well simulate the shape and posture of the female body and achieve a good effect of being able to try on clothes remotely [24]. Li et al. [25] proposed a robot model consisting of a flexible belt and an elastic rod as the main body and designed the pushing amount of the elastic rod and linear actuator according to the shape of the human body so that the flexible belt can effectively mimic the concave and convex situation of the human contour. Although Guo and li research can simulate diverse female body shapes, none have been designed for particular body postures (e.g., hunchbacked body postures) and the structural designs are often complex, resulting in high manufacturing costs that are not conducive to commercial use at scale. While these investigations can simulate diverse body shapes, the structural designs tend to be intricate, resulting in higher manufacturing costs.

This paper introduces an adjustable mannequin capable of continuously changing body postures, referred to as PAM. The design divides the standard mannequin into six parts and uses stepper motors to drive four of the movable parts, thus realizing the continuous posture adjustment function. Compared with the existing dynamic mannequins, the PAM design has the following advantages: the PAM can realize continuous adjustment between the chest-up and hunchback postures, and has higher relevance and accuracy for the simulation of chest-up and hunchback postures. Secondly, the PAM has a simple structure, low production cost, and is easy to mass-produce, which makes it practical and economical.

KEY INDICATORS OF CHEST-UP AND HUNCHBACKED BODY POSTURE CHANGES

When the body undergoes postural changes, all body parts experience varying degrees of alteration. Among these, chest convexity, back convexity, and the shoulder opening angle stand out as the three foremost key indicators. Illustrated in figure 1, chest convexity and back convexity are measured as the distances from the point of chest height and the point of the back bulge to the coronal plane (figure 1, *a*). Meanwhile, the shoulder opening angle is defined based on the motion of the sternoclavicular joint, specifically, the forward and backward swinging angle of the shoulder about the front neck point (figure 1, *b*). This angle is established by measuring the angle formed between the line connecting the front neck point and the acromion point, and the coronal plane. This angle alters corresponding to the extent of the chest-up or hunchbacked postural change.

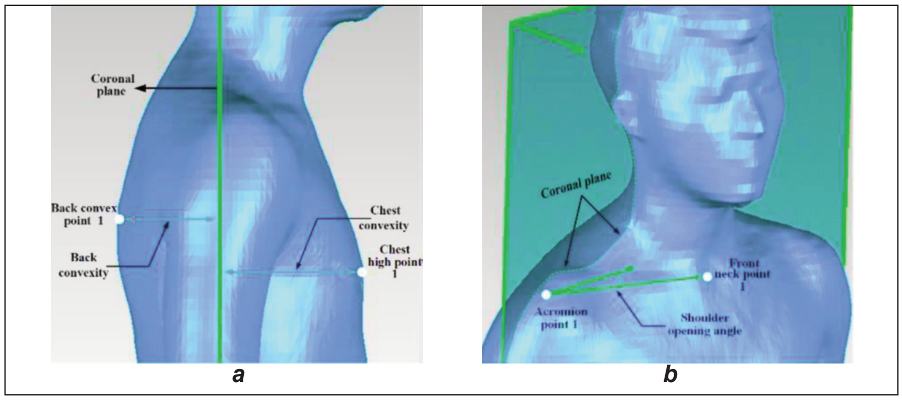

Fig. 1. Schematic diagram of key indicators for chest-up and hunchbacked posture changes: *a* – chest and back projection data; *b* – shoulder opening angle

To ascertain the direction and range of movement for the three key indicators of the mannequin in chest-up and hunchbacked postures, 17 young men whose body sizes closely matched the 180/96A mannequin were recruited as participants. They were instructed to be shirtless and to adopt a natural standing position as the baseline, a military stance for chest-up posture, and a writing stance at a table for the hunchbacked posture. Utilizing the X Scan 2017 Bock 3D body scanner, their upper bodies were scanned to obtain digital models, representing three different body types.

Table 1 lists the minimum and maximum values of the three key indicators obtained through the scanning of 17 men when the chest-up and hunchbacked posture changed. As can be seen from the table, the range of displacement for chest convexity is 2.2 to 35.9 mm, the range of displacement for back adduction is 1.7 to 19.8 mm, and the range of angle of the shoulder back swing is 0.04 to 16.89° in the upright position. In the hunchbacked posture, the range of inward displacement of the chest is 19.2 to 45.1 mm, the range of convex displacement of the back is 0.9 to 38.6 mm, and the range of forward swing angle of the shoulder is 0.39 to 10.72°. Indeed, we are more interested in the maximum values of the three key indicators in table 1 when body posture changes, using them as the range of variation in mannequin conditioning.

DESIGN AND FABRICATION OF POSTURE-ADJUSTABLE MANNEQUIN (PAM)

Design of panels

A standard male mannequin, sized 180/96A, was selected as the reference model and divided into six parts: neck, left shoulder, right shoulder, chest, back, and waist and abdomen, as depicted in figure 2. In figure 2, the neck panel is the part above the neck root circumference line and the waist and abdomen panel is the part below the chest circumference line, both of which are fixed and immobile. The cutting lines for the two shoulder panels are determined by diagonal lines intersecting from the lateral neck point to the opposite armpit, aligned adjacent to the fixed neck, the movable front chest, and the back panels, respectively.

The panels are cut with a sufficiently large gap along the cutting line to ensure that they do not come into contact with each other at the maximum range of motion. Through several adjustments, the gap

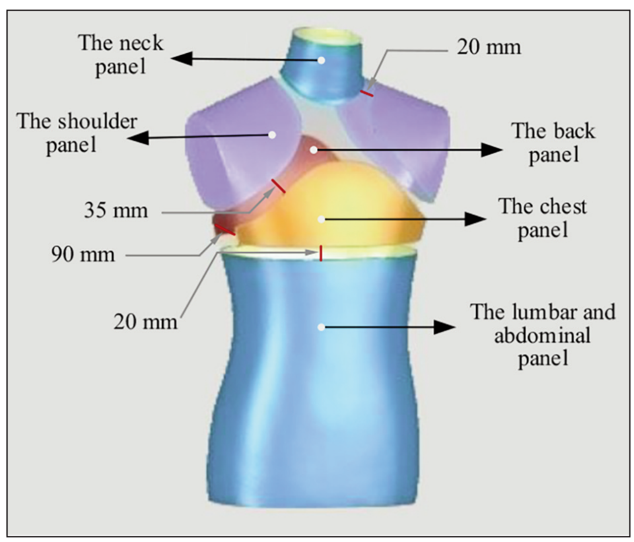

Fig. 2. Diagram of panel segmentation for the mannequin

Table 1

STATISTICAL TABLE OF KEY INDICATORS OF DIFFERENT POSTURES				
Measured items	**Chest up posture**		**Hunchbacked posture**	
	Minimum value	**Maximum value**	**Minimum value**	**Maximum value**
Chest convexity (mm)	2.2	35.9	19.2	45.1
Back convexity (mm)	1.7	19.8	0.9	38.6
Shoulder opening angle (°)	0.04	16.89	0.39	10.72

between the neck panel and the shoulder panel was determined to be 20 mm, the gap between the shoulder panel and the chest back panel to be 35 mm, and the gap between the chest back panel and the lumbar and abdominal panels to be 20 mm. due to the large range of motion of the chest and back, their clearance in the armpits was determined to be 90 mm.

Design of mechanical structures

Figure 3 depicts a schematic diagram detailing the mechanical structure within the mannequin. In figure 3, *a*, four stepper motors are secured in the lower section. Specifically, the two central motors facilitate the forward and backward movements of the chest and back modules via gears and racks, while the two motors on either side rotate the oscillating bar through a gear set to achieve the retraction and release movements of the left and right shoulder modules. The mechanism's connection to each moving panel is illustrated in figure 3, *b*. Notably, despite the two racks not being centred on the chest and back panels, the design allows the chest and back panels to move backwards and forwards in parallel. This is feasible due to one end of the rack being anchored to the panel, which possesses rigidity.

Assembly of the structure

Figure 4 shows the different body posture effects of the assembled mannequin. The mannequin can be well changed continuously from a chest-up posture (figure 4, *a*) to a standard normal posture (figure 4, *b*) and a hunchbacked posture (figure 4, *c*). Although there are gaps between the movement modules of the panel, these gaps are covered when wearing the designed elastic fabric skin (39% spandex), and a smoother transition between the modules can be achieved, even at maximum movement, and the gap areas between the modules remain smooth. In addition, these gaps are in the area of the scapula to the underarm line and the lower bust loop, which are not critical areas of the garment and therefore have little impact on their use in the garment-making process.

VALIDATION OF VALIDITY BY 3D SCANNING

We have examined the effectiveness of the use of PAM posture changes by using 3D scanning technology and actual garment making.

Two men, possessing body shapes akin to a standard mannequin, were separately recruited for 3D scanning. One exhibited a habitual chest-up posture, while the other displayed a hunchbacked posture. The aim was to acquire 3D scans and contour curves of pivotal cross-sections. The resulting contour curves were compared to the scanned contour lines of the PAM under standard, chest-up posture, and hunchbacked posture respectively.

Figure 5 illustrates the comparison of the body curves of the man with a chest-up posture and three critical cross-sectional contour curves of the PAM in the standard posture and the chest-up posture. In this figure, the curve of the chest-up man's body is depicted as a black solid line, the standard posture of PAM is represented by a red dotted line, and the chest-up posture of PAM is indicated by a blue dashed line. As observed in the comparison of shoulder cross-sectional profile curves in figure 5, *a*, the PAM successfully diminishes the 8 mm depression near the anterior middle of the normal posture to 2 mm. Furthermore, it diminishes the 25 mm convexity in the posterior middle to 12 mm, consequently reducing the convexity at both scapulae from 12 mm to below 4 mm. In the comparison of the chest convex section shown in figure 5, *b*, the PAM reduces the depression of the two

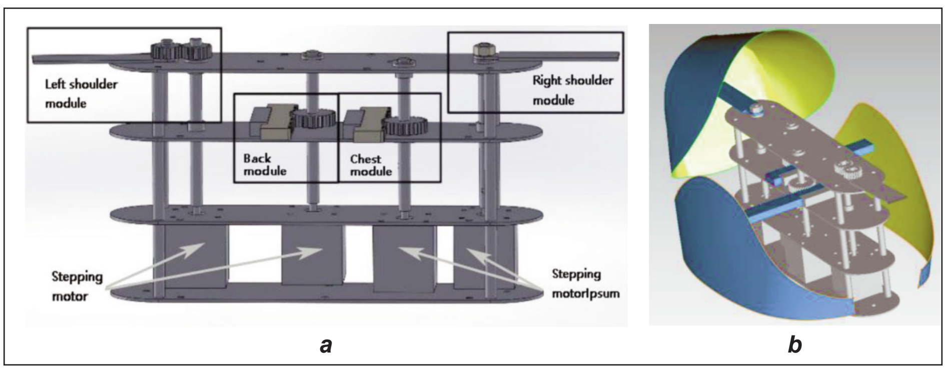

Fig. 3. Diagram of mechanical structure and installation: *a* – mechanical structure; *b* – installation diagram

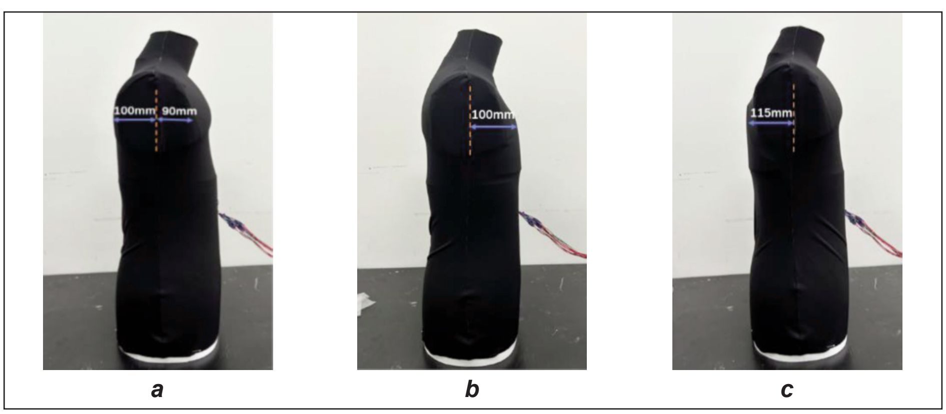

Fig. 4. The posture-adjustable mannequin: *a* – distance between the front and back of the chest in the standard state; *b* – chest protrusion/chest up posture state; *c* – back protrusion in hunchbacked state

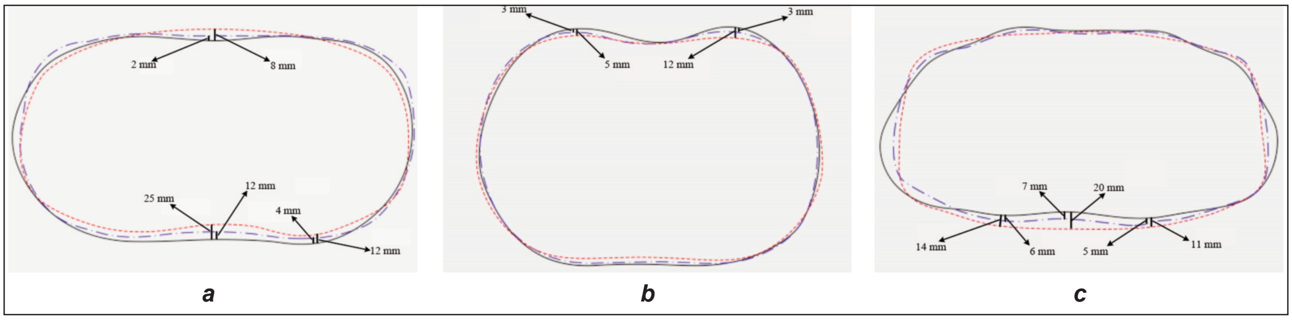

Fig. 5. Comparison of contour curves for three critical sections between PAM and the man in chest-up posture (black solid line – the curve of the chest-up of the human body; red dotted line – the curve of the standard posture of PAM; blue dashed line – the curve of the chest-up posture of PAM): *a* – shoulder cross-section; *b* – chest convex cross-section; *c* – back convex cross-section

chest convex points measuring 12 mm and 5 mm to below 4 mm. In the cross-sectional view of the back convexity illustrated in figure 5, *c*, the PAM decreases the 20 mm convexity at the rear centre that is present in the normal posture to 7 mm. Similarly, the convexity at each back convexity point is reduced from 14 mm and 11 mm to 6 mm and 5 mm, respectively.

Figure 6 illustrates a comparison of crucial cross-sectional profile curves between the hunchbacked man and the PAM. The shoulder cross-section contours presented in figure 6, reveal that the standard posture of the PAM (depicted by the red dashed line) and the contour of the human body (indicated by the black solid line) both exhibit a convexity of 12 mm in the front-middle region and an 8 mm convexity in the back-middle region. Through adjustments to the PAM's body posture, the convexities in the front-middle and back-middle areas (illustrated by the blue dashed line) can be eliminated. Figure 6, *b* displays the cross-sectional profile of the chest. In the standard PAM posture, two chest convexities are observable, but these can be eradicated by altering the PAM's body shape. Moreover, the concavity in the posterior middle area can be diminished from 16 mm to 8 mm. In the back cross-sectional profile depicted in figure 6, *c*, the PAM successfully removes the 22 mm convexity in the mid-front area, along with the 6 mm concavity present at the two back convexities in the standard PAM posture.

By utilizing scans and conducting comparative analyses of actual male bodies, it can be deduced that the PAM can effectively emulate and accommodate diverse body forms. During the chest-up posture, the PAM can minimize the chest's concavity, the inward curvature of the back, and the rearward shoulder angle, thus approximating the standard body posture. When in the hunchbacked posture, the PAM can mitigate the shoulders' and chest's convexity while eliminating the back's concave curvature, thus achieving the attainment of a more harmonized posture. These results demonstrate the adaptability and effectiveness of the PAM in simulating and adjusting to realistic body postures.

GARMENT-MAKING AND TESTING

A comparison was conducted between a hunchbacked body posture and a standard body posture (standard mannequin) on the PAM through the draping method. Shirt garment patterns, incorporating an ease allowance of 8 cm, were designed, and garments were created for both the hunchbacked and normal body postures. Figure 7 illustrates a comparison between garment patterns for the two body postures. The dashed line corresponds to the normal body posture, while the solid line represents the hunchbacked body posture. The chest line serves as the horizontal reference, aligning the front piece with the front centre, the back piece with the back centre, and the sleeve pieces with the cuff line. The disparities are evident in the diagrams: in figure 7, *a*, notable expansion can be observed in the width of the hunchbacked posterior piece, the armhole line, and the yoke line. The posterior collar line and shoulder line

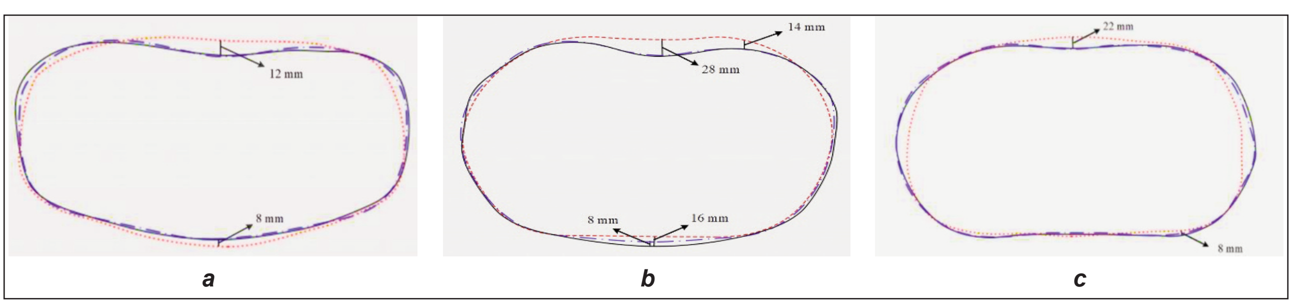

Fig. 6. Comparison of contour curves for three critical sections between PAM and the man in hunchbacked posture (black solid line – the curve of the hunchbacked posture of the human body; red dashed line – the curve of the standard posture of PAM; blue dashed line – the curve of the hunchbacked posture of PAM): *a* – shoulder cross-section; *b* – chest convex cross-section; *c* – back convex cross-section

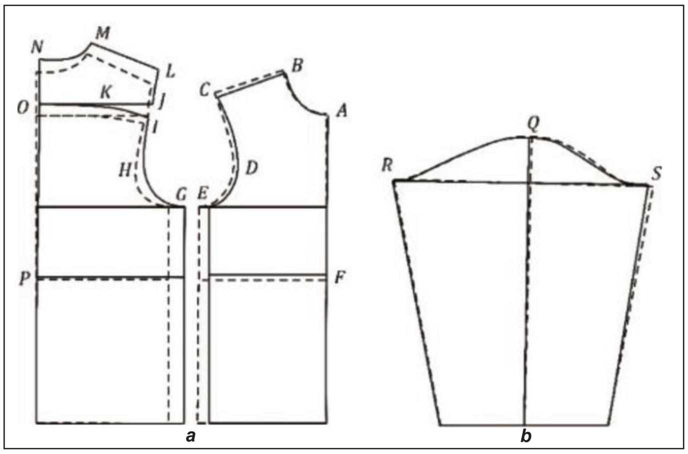

Fig. 7. Shirt paper pattern comparison (dashed line for normal posture, solid line for hunchback posture): *a* – front and back pieces; *b* – sleeve pieces

of the yoke piece have also expanded, along with an increased width in the yoke area where the yoke and posterior piece intersect. In contrast, the width of the front piece, the armhole line, and the shoulder line have proportionately narrowed. From the comparison of sleeve pieces in figure 7, *b*, it can be observed that there is little change in the sleeve pieces between the hunchbacked posture and the normal posture, and the hunchbacked pattern only has a slight retraction in the front and back sleeve width. Overall, when transitioning from a normal to a hunchbacked posture, the garment patterns widen and lengthen across the back piece's width and length, while the front piece experiences narrowing and shortening. These modifications align with the corrective adjustments proposed by Zhang et al. [13] for garment paper patterns

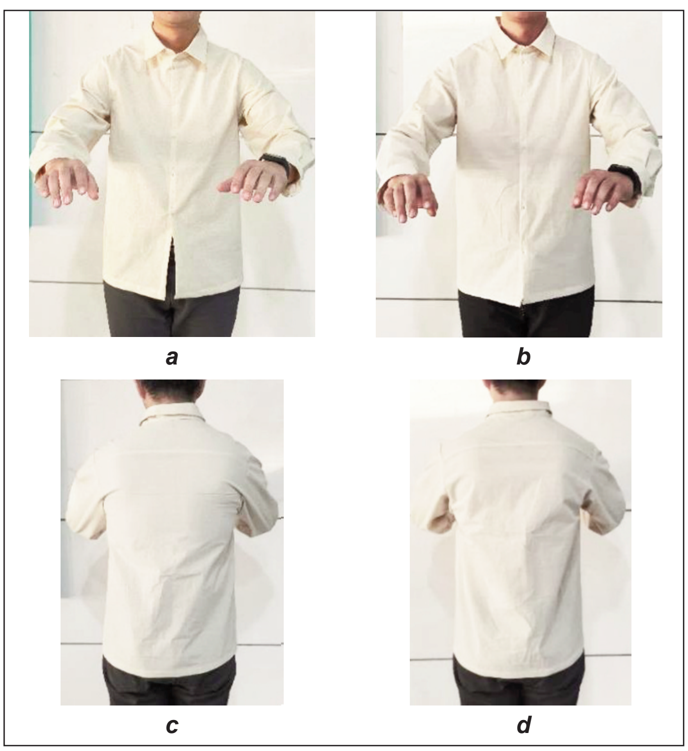

Fig. 8. Comparison of the shirt's appearance when worn: *a* – effect of the standard shirt, front view; *b* – effect of the hunchbacked shirt, front view; *c* – effect of the standard shirt, back view; *d* – effect of the hunchbacked shirt, back view

tailored to unique body types. The amount of change determined through the use of PAM is more precise.

To visually show the effect of the PAM, the body size of the mannequin was adjusted to simulate the body posture of a slightly hunchbacked person.

Subsequently, a shirt representing a slightly hunchbacked posture and another in a standard body posture was crafted. From the front perspective, the standard shirt depicted in figure 8, *a* exhibits an excess of fabric on the front chest, marked by a diagonal crease extending from the shoulder to the centre front. Numerous folds gather at the front shoulder, and a substantial diagonal wrinkle emerges at the armhole, consequently leading to inadequate closure of the placket at the bottom hem. In comparison when donning the shirt tailored to a hunchbacked posture (figure 8, *b*), there is less fabric build-up on the front chest, fewer shoulder creases, and diagonal stripes at the armholes, and the centre front placket closes well.

From the rear perspective, the standard shirt's rear fabric appears taut, and a conspicuous diagonal stripe is visible at the shoulder sleeves. This observation suggests that the shirt, in this condition, exerts pressure on the hunchbacked body's back, significantly compromising both comfort and aesthetics (see figure 8, *c*).

Conversely, when donning the hunchbacked shirt (figure 8, *d*), the fabric's tightness on the body's rear is markedly ameliorated, and the raglan design on the shoulder sleeves is eradicated. This alteration provides ample room for back movement and enhances the garment's aesthetic appeal.

Consequently, individuals with a habitual hunchbacked posture may encounter discomfort while wearing a standard shirt during everyday activities (such as the previously mentioned office tasks). However, by leveraging the PAM to design a garment tailored to their posture, this inconvenience can be substantially alleviated, thereby enhancing both the garment's fit and aesthetic appeal. Individuals with a habitual chest-up posture face a comparable issue, which can be similarly addressed through targeted application of the PAM.

Combining the above results, this article divides the standard-size human platform into 6 parts and uses mechanical structures to design motion control for 4 of them. It can simulate the most common posture changes of the human body, such as chest-up and hunchbacked postures. The crafted posture-adjustable mannequin can achieve posture alterations without necessitating changes in mannequin dimensions. This design has the advantages of high accuracy of size, accurate body simulation, easy to make and control and low cost, and the benefit of easy support for the transformation of clothing customization of small and medium-sized enterprises.

CONCLUSION

Mannequins play a pivotal role in garment design and production. This paper divides the standard mannequin into six modules: neck, front chest, back, left and right shoulders, and waist and abdomen. By using stepper motors to drive the four modules of the front chest, back, and left and right shoulders respectively, a mannequin is created that can continuously change its posture from chest-up to hunchbacked. The extent of motion for each module was established through the measurement of posture alteration data from 17 men. A comparison of the 3D scans shows that the PAM fits well with the corresponding posture of the real man in several cross-sections. Simultaneously, a comparison of the draping cut-out patterns revealed that for the humpbacked body, the patterns produced a change in the width and height of the back piece and a narrowing and shortening of the front piece. Furthermore, by comparing the wearing of real clothes on hunchbacked individuals, the results also show that the PAM can produce better-fitting shirts, significantly improving the inconvenience of standard clothing when performing certain common movements. From a commercial standpoint, the PAM, enabling continuous postural adjustments encompassing chest-up and hunchbacked poses, can substitute multiple static mannequins while bolstering the personalized clothing business model.

The research in this paper has room for improvement due to objective constraints. During the process of chest and back posture changes, the neck lumbar and abdominal regions also change to maintain the center of gravity balance. This paper focuses on the changes in the shoulders, chest and back, and will further investigate the changes in the neck, waist and abdomen of the hunchback and chest posture in the future. By increasing the corresponding mechanical structures of the neck, waist and abdomen as well as the number of movable panels, the simulation effect of the body-adjustable mannequin will be improved.

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Authors:

GUODONG XU, YUJIA REN, YU CHEN

School of Textiles and Fashion, Shanghai University of Engineering Science, China

Corresponding author:

Dr. YU CHEN
e-mail: ychen0918@sues.edu.cn