Draft-Space Warping:
Grading of Clothes Based on Parametrized Draft

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Abstract

This paper presents a novel framework for garment grading. In CG, an extensive amount of study has been done to clothe human characters, but little attention has been taken to the grading problem itself. For the development of a grading technique, we got the insight from the process of drawing the pattern-making draft (sloper) in the clothing field. Noting that the draft can be completely determined by supplying the primary body sizes, we abstract the draft construction process as a computer procedure which we call the *parameterized draft*. With the parametrized draft, we develop a grading method based on the draft-space warping, which takes three steps: (1) draft-space encoding, (2) target draft construction, then (3) draft-space decoding. The proposed grading method can be performed instantly for any given body without calling for the user's intervention. With experimental results, we show that the new grading framework can bring an improvement to garment grading.

Keywords: garment grading, mean value coordinates, clothing simulation, clothing design retargeting

1 Introduction

In the clothing production, a garment is usually designed for a specific/standard body, and then the result is modified to fit different bodies. The latter part is referred to as grading. Without grading, the design cannot be appreciated by other bodies. Therefore, grading is very im-

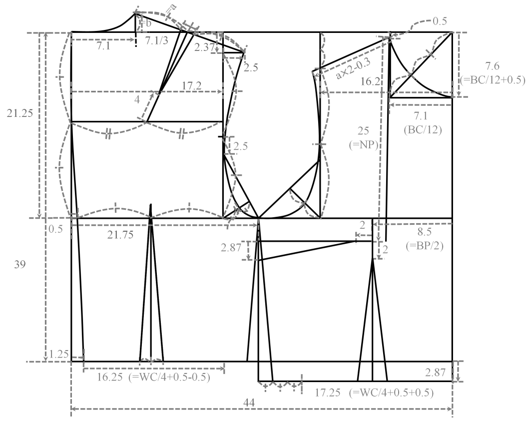


Figure 1: A pattern-making draft for the bodice.

portant in the clothing field. In CG, an extensive amount of work has been exerted to clothe human characters, but little study has been performed on the grading problem itself.

Although the word 'design' is used comprehensively, in this work where the main focus is grading, we will use the term 'garment design' more specifically; a garment design refers to a set of panels $[p_1, p_2, \ldots, p_N]$ which are stitched at the sides. Note that determination of the shape and size of the panels and the stitches among them forms the essential part of the garment de-

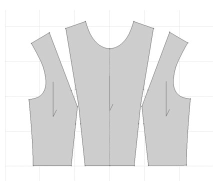


Figure 2: A set of panels created based on the draft shown in Figure 1.

sign, but the color and prints of the textiles are irrelevant in the consideration of grading. In this work, the distinction between 'pattern-making draft' and 'panel' is needed. Pattern-making is the process of drawing the pattern-making draft (sloper) as shown in Figure 1 for the purpose of obtaining a panel. As shown in Figure 2, a panel is a piece of *cloth* which is created based on the pattern-making draft. In this work where the garment is reproduced with the CG technology, each panel has to be represented on the computer. Thus, speaking in terms of data, a panel is represented by a set of points and lines. For the given panel, a grading algorithm has to generate a new panel (i.e., a new set of points and lines) which is supposedly fit the given target body.

The two grading methods, namely, the cut-and-spread method and the pattern shifting are in use in the current clothing industry [12]. When the original panel is given, those methods generate graded panels by applying translations to the panel vertices according to the predetermined directions by the predetermined amounts given in the rule table. We will call this sort of grading as *linear grading*, since the translations are usually made along a straight line. Unfortunately, the linear grading may not be an optimal treatment to accommodate non-linear, non-planar body variations. The above problem has been noted for a long time. In luxury brands, therefore, a grading expert makes further adjustments to the linearly graded results, which is typically a time consuming and labor-intensive task. This paper is motivated from the author's belief that such non-linearity can be better accounted for by a computer program rather than human hands.

Grading can be thought of as the following retargeting problem.

Given:

- A garment design, i.e., a set of panels $\Phi(A) = [p_1, p_2, \ldots, p_N]$ prepared for a specific body A.
- The target body B whose specifics are given with the primary body sizes (PBSs). The PBSs of three example target bodies are shown in Table 1.

Find:

- A new version $\Phi(B) = [\hat{p}_1, \hat{p}_2, \ldots, \hat{p}_N]$ which comprises the same design, but fits to the target body B.

For the development of a grading technique, we got the insight from the process of drawing the pattern-making draft (or just draft from now on). From the given PBSs, a clothing expert can construct the draft by drawing points or straight/curved lines step by step. For example, Figure 1 is drawn from the first six PBSs of the source body shown in Table 1. Since the draft is completely determined from the PBSs, we can abstract the construction process as a computer procedure $D(*)$ which takes an arbitrary body then generates the draft for it. We call that procedure the *parameterized draft*. For example, Figure 1 is $D(A)$ for the body A summarized in the Source column of Table 1.

2 Related Work

In the computer graphics field, the study on the grading technique is in the early stage. Volino et al. [10] presented an interactive garment modeling system in which the garment could be edited in 3D, then its constituent 2D patterns can be extracted. Umetani et al. [8] presented a method in which the 3D garment and its constituent 2D patterns are coupled in such a way that an interactive modification of one results in immediate modification of the other. When viewed from the clothing industry, both methods are revolutionary, since they allow clothing construction in 3D and produce the 2D patterns of the fitted garment. However, we do not categorize them as grading techniques, since accommodating the body variations was not the main concern of those methods.

Wang et al. [2] proposed a garment retargeting method which established the spatial relationship between the garment and the source body. The original garment is then retargeted to the target body following the spacial relationship established above. Another automatic garment resizing method proposed by Meng et al. [14] solves the distortion problem of [2] by introducing a local geometry encoding technique. Recently, Brouet et al. [11] presented a garment transfer method performs garment grading by explicitly considering additional criteria such as the silhouette, fit, manufacturability.

In the goal, our work is same with the above three methods; they develop methods that retarget a given garment design to fit the target body while preserving the original design. In the methodology, however, our work is different from the above methods; while the above methods make a direct retargeting of the garment in 3D with the subsequent pattern extraction process [1], our method retargets each 2D panel to the graded version via the 2D pattern-making draft space, resulting in more utilization of the pattern-making expertise from the clothing field.

The essence of the draft-space encoding is expressing the position of each panel vertex as a weighted sum of the draft vertices. A variety of such encoding schemes have been studied. One of the simplest approaches is triangular barycentric coordinates system (TBC). Many researchers have used TBC and attempted extension of it for their own purposes [3] [4]. Floater [7] introduced the mean value coordinates (MVC) which could encode a position with respect to an n-gon. The weights of MVC can have negative values when the n-gon is concave. The harmonic coordinates [9] and the positive mean value coordinates (PMVC) [13] were proposed to achieve the non-negativity. Among the above encoding methods, MVC and PMVC are the most relevant to our work. The details of those two methods will be introduced in Section 5.

3 Introduction to the Parameterized Draft

Pattern-making is the science to find out the panels which constitute a given design. An important requirement imposed for the pattern-making is that the resultant garment should fit the target body. To answer for the fitting part, the fashion field has been using the drafting from a long time ago. In fact, drafting is a common element practiced from fashion schools. The fashion institutes (e.g., SADI, SMOD) have established their own ways of drafting the basic bodice, skirt, sleeve, pants, etc. A draft is used as the starting point of many different designs. For example, virtually all the female tops can be derived from the basic bodice draft. We note that, when the drafting is developed as a computer procedure (parametrized draft), a draft can be constructed instantly, which can take tens of minutes even to an experienced pattern-maker.

Although the idea itself is simple, we note that to our knowledge this work is the first attempt to utilize the parametrized draft for the purpose of grading. Conventionally, grading is used for mass production. For example, when a medium size garment is designed, grading is done for obtaining the large and small versions of it. The proposed grading framework based on the parametrized draft is far more powerful than the conventional grading, since it can instantly perform grading for any body size without calling for the user's intervention. In clothing, mass customization has been conceived as a dream technology which can provide made-to-measure quality garments at the cost comparable to ready-made garments. The authors believe that the proposed grading method based on the parametrized draft can be an important element for the realization of the mass customization.

4 Draft-Space Warping

With the parametrized draft presented in Section 3, now we develop a novel grading scheme which we call the *draft-space warping* (DSW). Input to the DSW is the source panels $\Phi(A) = [p_1, p_2, \ldots, p_N]$ (i.e., the design constructed for the standard body A) *positioned* in reference to the source draft $D(A)$. The position of the panels $p_1, p_2, \ldots, p_N$ with respect to the draft is important, because the essence of DSW is to keep the $D(A)$-relative positions invariant during the $D(A)$-to-$D(B)$ space warp. We assume that the design $\Phi(A)$ is created in reference to the draft $D(A)$ (the *panel-draft coupling assumption*), in which case the panels are already positioned on that draft.[1]

The DSW is done in three steps. In this section, we show how a single panel p_k is graded with the DSW. Then, the whole design can be graded by applying the same algorithm to each panel. Let P_{kj} $(j = 1, \ldots, L)$ be the vertices of the panel p_k. Let v_i $(i = 1, \ldots, M)$ be the vertices in the source draft $D(A)$.

[1] When $\Phi(A)$ is not created in reference to the draft $D(A)$, then positioning of the panels with respect to that draft can be a problem. Since it is a common industry practice to perform panel creation in reference to a draft, making the panel-draft coupling assumption does not significantly limit the applicability of the proposed grading method.

Draft-Space Encoding: This step encodes the position of each panel vertex P_{kj} with respect to $D(A)$. In this work, we encode P_{kj} by expressing it as a linear combination of the draft vertices.

$$P_{kj} = \sum_{i=1}^{M} \lambda_i v_i. \tag{1}$$

More specifically, this step finds out the weight vector $(\lambda_1, \ldots, \lambda_M)$ for each panel vertex P_{kj}. When $M > 3$, (in most drafts $M >> 3$), the linear combination is not unique, thus encoding may not be well-defined. Fortunately, there have already been pioneering studies which can be applied to our draft-space encoding. The details of the draft-space encoding are postponed to Section 5.

Target Draft Construction: In this step, we generate the target draft $D(B)$ of the source body B, which is a trivial task when the parametrized draft is available. Let $\hat{v}_i$ $(i = 1, \ldots, M)$ be the vertices of the target draft $D(B)$.

Draft-Space Decoding: This step finds out the new vertex position $\hat{P}_{kj}$ of the graded panel $\hat{p}_k$. With the assumption that the relative position (i.e., encoding) of each panel vertex P_{kj} is invariant during the $D(A)$-to-$D(B)$ space warp, we compute $\hat{P}_{kj}$ with

$$\hat{P}_{kj} = \sum_{i=1}^{M} \lambda_i \hat{v}_i. \tag{2}$$

Here the weights λ_i are the ones which were calculated in the draft-space encoding step.

The reason why the above simple encoding-then-decoding operation can perform the grading task can be attributed to the fact that the target draft (generated with the parametrized draft) already contains all the necessary scalings to cover the source-to-target body mismatches.

5 Draft-Space Encoding

In this section, we present the draft-space encoding method which is an important component in the development of the proposed grading framework DSW. This section reviews previously proposed candidates for the draft-space encoding, then concludes with an encoding method which best suits for the current purpose.

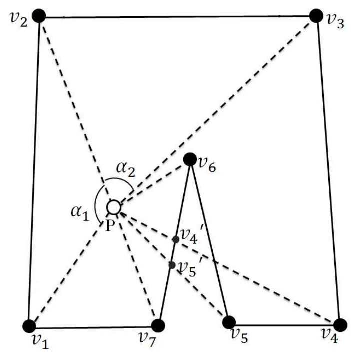


Figure 3: Calculating the mean value coordinates

The triangular barycentric coordinates (TBC) is one of the most popular methods which have been used for encoding a position within a triangle. Unfortunately, a typical situation the draft-space encoding has to handle is the one shown in Figure 3, which is far from a triangle. Several techniques have been proposed which can directly encode a position with respect to a general n-gon without going through triangulation [4], [5], [7]. Suppose that an n-gon consists of M vertices $v_1, \ldots, v_M$ on the same plane (in the counter-clockwise order), and we want to encode a position P on that plane as a linear combination of those vertices (Figure 3)

$$P = \sum_{i=1}^{M} \lambda_i v_i \ , \quad \sum_{i=1}^{M} \lambda_i = 1. \tag{3}$$

Floter [7] introduced a weighting scheme, so-called the mean value coordinates (MVC)

$$\lambda_i = \frac{w_i}{\sum_{k=1}^{N} w_k} \ , \ w_i = \frac{\tan(\alpha_{i-1}/2) + \cot(\alpha_i/2)}{\|v_i - P\|^2}, \tag{4}$$

where α_i is the angle made by v_i's and/or P as shown in Figure 3. The method is named that way because the weights are determined by applying the mean value theorem to the harmonic functions. The encoding quality of MVC is reported superior to other encoding methods [5].

When the n-gon has concavity as in the case of Figure 3, with the MVC, the weights for the invisible vertices (for example, in Figure 3, v_4 and v_5) can have negative values. Lipman et al.[13] proposed the positive mean value coordinates (PMVC) to cope with that problem, in which the linear combination does not include

v_4 and v_5 but includes their clamped versions v'_4 and v'_5. A variation the authors additionally experimented in this work for achieving the non-negativity was omitting those vertices in the summation. We will refer to this variation the *omitted mean value coordinates* (OMVC). PMVC and OMVC exhibit different behaviors in coping with the concavities but both show reasonable encoding performances.

We turn to another challenge in the development of the draft-space encoding method. In designing a garment, a panel vertex may in general come exterior to the draft. More specifically, a panel vertex may not lie within the convex hull of the draft vertices. Therefore, another characteristic the draft-space encoding method should equip is the capability of handling the outliers.

If the non-negativity should be imposed in encoding the outliers, then it is imperative to create a number of extra vertices (we call them the *ghost vertices*) in addition to the original draft vertices. We have experimented several ways of creating ghost vertices in the context of PMVC and OMVC. But neither of them produced satisfactory results. For both PMVC and OMVC, the weights could vary non-continuously across the draft. More fundamentally, (1) the ghost vertices are extraneous information which is not in the original pattern-making expertise, and (2) creating them ruins the clear decomposition between the draft construction and the draft-space encoding, which is the key attraction of the proposed grading framework. Therefore, we conclude to give up the non-negativity in the development of the draft-space encoding.

When we decide not to create ghost vertices, then we can rule out PMVC and OMVC from the candidates, since neither of them are capable of expressing the outliers. Interestingly, among the encoding methods which have been proposed so far, we find that the MVC, which can have negative weights, is to our knowledge an optimal choice when the outliers are considered as well as the concavities. We find that the negativity of MVC does not work harmfully for the draft-space encoding. With the MVC, the weights vary continuously across the interior and exterior of the draft.

(a) Source (b) Target 1 (c) Target 2 (d) Target3

Figure 4: The source and three target bodies

6 Results

We implemented the method presented in this paper on an Intel Core i7 3.20GHz CPU with a NVIDIA Geforce GTX560 GPU. To test the proposed grading method, we constructed two outfits, a one-piece and a minidress as shown in Figure 9 (4) a and Figure 8a. The one-piece was used for the silhouette analysis, the garment pressure analysis, and the air-gap analysis. The minidress was use to demonstrate that the proposed method can process complex garments. We used a physically-based clothing simulator for the above analyses which is developed based on [6].

For both of the above dresses, running the whole grading algorithm including the draft-space encoding, target draft generation, and draft-space decoding took less than one millisecond. Therefore, we will not give any further time analysis for this work. Figure 4 shows the source body and three target bodies used for the experiments. The PBSs of those bodies are summarized in Table 1. For the one-piece experiment, the source draft shown in Figure 9 (1) a was created for the source body using the parametrized draft. Referring to the draft, a fashion designer created the source panels shown in Figure 9 (2) a. This panels were the input to the proposed grading system.

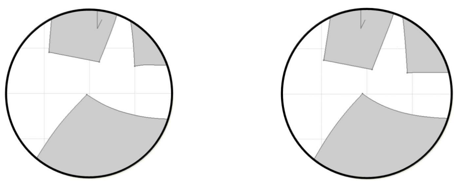
6.1 Generation of Target Drafts

Three target drafts were generated with the parametrized draft for the three target bodies as shown in Figure 9 (1) b-d. Clothing experts judged that our parametrized draft successfully implements the conventional drafting steps.

PBS (unit:cm)	Source	Target 1	Target 2	Target 3
Bust Circumference	85.0	80.0	95.0	105.0
Waist Circumference	65.0	60.0	75.0	85.0
Hip Circumference	90.0	85.0	100.0	110.0
Waist Back Length	39.0	38.4	40.2	41.4
Bust Point to Bust point	17.0	16.4	18.2	19.4
Neck Point to Breast Point	24.0	23.2	25.6	27.2
Skirt Length	55.0	53.0	59.0	59.0
Hip Length	19.0	18.4	20.2	21.4
Height	171.0	169.5	174.0	177.0
Front Armhole Circumference	20.2	19.6	21.4	22.6
Rear Armhole Circumference	21.4	20.8	22.6	23.8
Sleeve Length	54.0	53.4	55.2	56.4
Wrist Circumference	20.0	19.4	21.2	22.4

Table 1: The primary body sizes for the source and target bodies

6.2 Generation of Panels



(a) DSW grading (b) Manual grading

Figure 5: Magnified view of the DSW and manual grading in the case of Target 3

Figure 9 (2) b-d show the results of running the DSW grading for Targets 1-3, respectively. Figure 9 (3) b-d show the results of the manual grading for Targets 1-3, respectively. the manual grading is linear grading followed by hand adjustments and it took about an hour. Viewed in that scale, no particular difference is noticeable. In a magnified view, some differences are noticeable, Figure 5 showing one example. It was difficult for a grading expert to tell which is the better result.

6.3 Silhouette Analysis

Figure 9 (4)-(5) and Figure 10 (1) show snapshots taken during the physically-based simulation of the ungraded, DSW-graded, and manually-graded versions, respectively. The results of ungraded show that each garment did not fit to each Target, it were too loose (Figure 9 (4) b) or tight (Figure 9 (4) c-d). Otherwise, the results of DSW-graded and manually-graded show that the garments well fitted Targets as shown in Figure 9 (5), Figure 10 (1). The results of DSW-graded is almost indistinguishable from those of manually-graded. We also note that the silhouette of the source design is kept quite well in the graded results of Figure 9 (5) and Figure 10 (1).

6.4 Pressure Analysis

During the physically-based clothing simulation, the simulator could calculate the cloth-to-body pressure distribution across the garment. Figure 10 (2)-(4) show the pressure distribution in the ungraded, DSW-graded, manually-graded versions, respectively. The highest and lowest pressure were shown in red and green. In the pressure distribution, the ungraded version was noticeably different from the DSW-graded and manually-graded versions, but the latter two versions were similar. We also note that the pressure distribution of the source design is kept quite well in the graded results of Figure 10 (3) and Figure 10 (4).

6.5 Air-Gap Analysis

During the physically-based simulation, we put a horizontal plane and obtained the cross-sections it makes with the body and the garment. In Figure 7, the body and the garment cross-sections are shown in gray and red, respectively. When those cross-sections are available, the air-

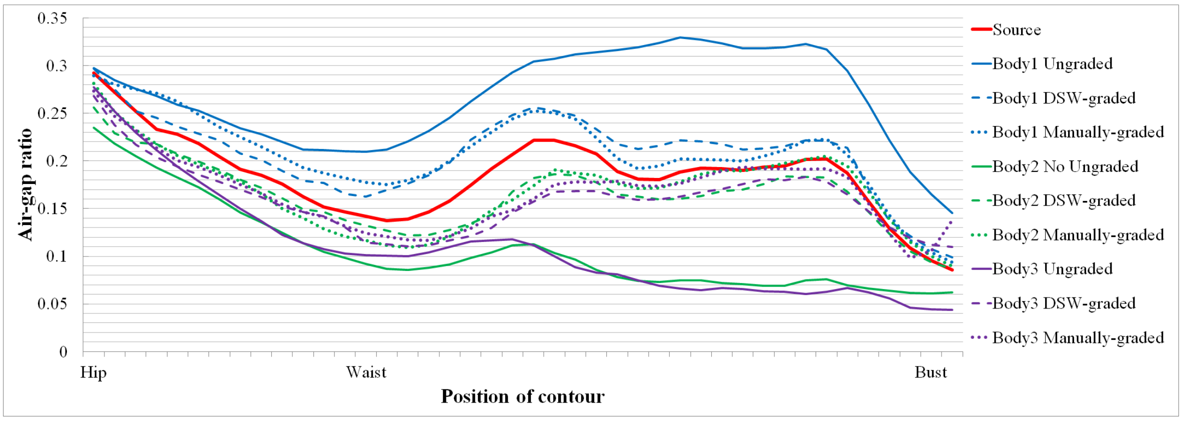


Figure 6: Comparison of the airgap ratio in various graded results

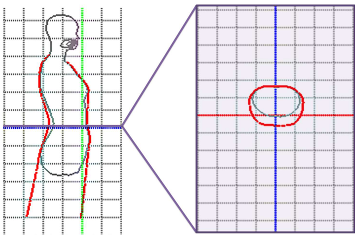


Figure 7: Air-gap analysis

gap ratio R can be defined as

$$R = \frac{A_{\text{garment}} - A_{\text{body}}}{A_{\text{garment}}}, \tag{5}$$

where A_{garment} and A_{body} are the areas enclosed by the garment and body the cross-sections.

Figure 6 plots the air-gap ratio at different elevations from hip to bust. The air-gap ratio of the source dress on the source body is plotted with red solid line. The air-gap ratio for the ungraded, DSW-graded, and manually-graded versions are solid, dashed, dotted lines. The results for the Targets 1-3 are shown in blue, green, and violet, respectively. It was observable that the air-gap ratio of the non-grading version was significantly different from the DSW-graded and manually-graded versions. But, the air-gap ratio of both DSW-graded and manually-graded versions were similar to that of the source dress/body.

6.6 Handling Complex Garments

We applied our method to a somewhat complex dress shown in Figure 8a. The proposed DSW grading algorithm successfully generated the graded versions for arbitrary bodices as shown in Figure 8b-d.

(a) (b) (c) (d)

Figure 8: Draping the minidress on the source body and arbitrary bodies

7 Conclusion

In this work, we presented a novel framework for garment grading. For the development of the grading technique we got the insight from the process of drawing the pattern-making draft. Noting that the draft can be completely determined from the primary body sizes, we abstracted the draft construction process as a procedure which we call the parameterized draft. With the parametrized draft, we developed the grading method which takes three steps: (1) draft-space encoding, (2) target draft construction, then (3) draft-space decoding. After investigating a few candidates for the draft-space encoding, we concluded that the mean value coordinates is an optimal choice.

The proposed method has been implemented and tested for grading a few garments. The silhouette analysis, the pressure analysis, and the air-gap analysis were performed on the graded results. We verified that the results are indistinguishable from the manually-graded results in the quality but taking much less time. In this work the grading quality was analyzed only with the physically-based simulator. As a future work, for the industrial validation of the method, the grading quality needs to be tested with real garments by putting them on the real subjects.

Realization of mass customization in the fashion field requires a grading technique which can generate the graded results for the given PBSs without any user's intervention. We note that the proposed grading framework based on the parametrized draft meets such condition and can bring a remarkable improvement to the clothing field.

Acknowledgements

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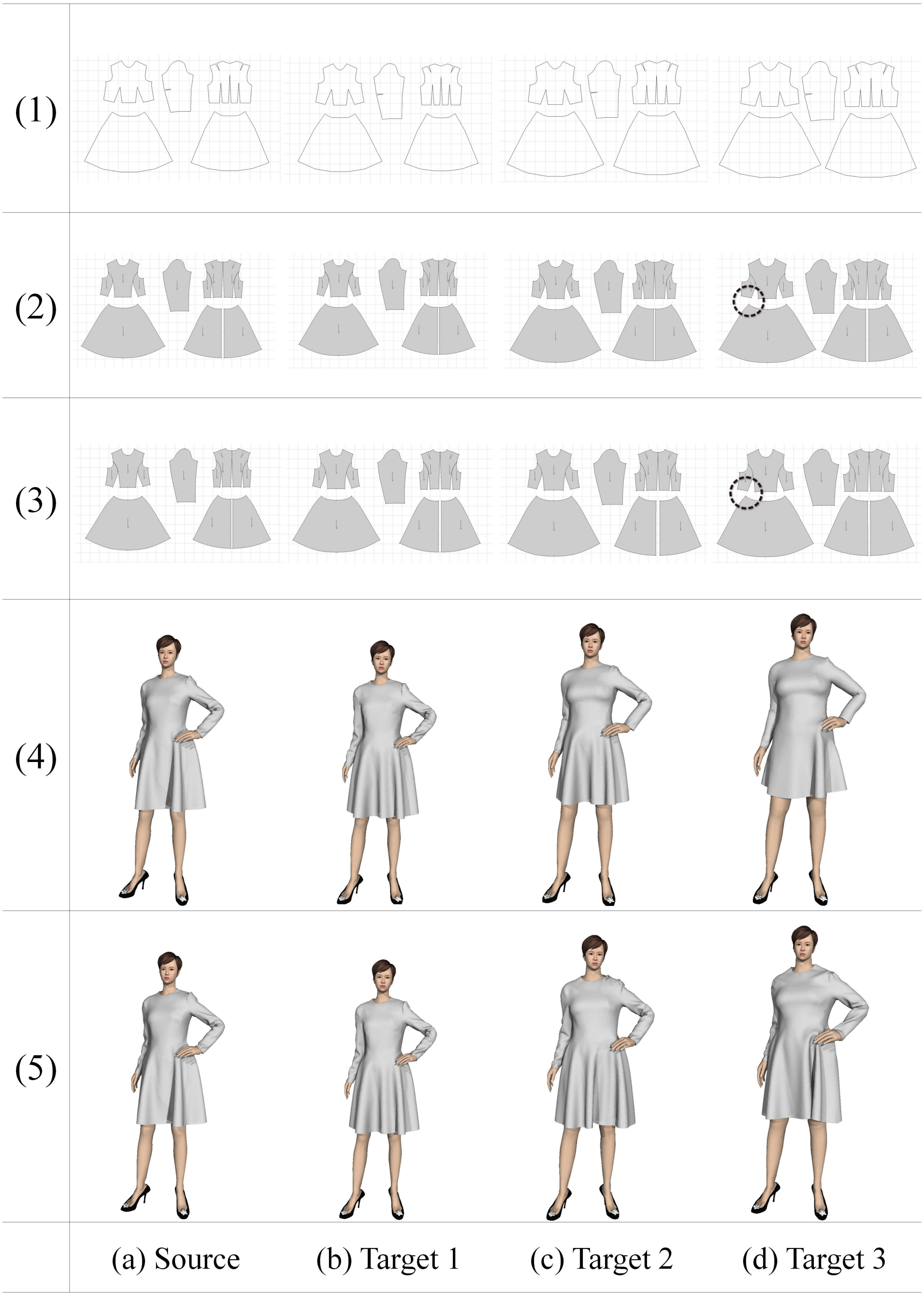

Figure 9: Result figures 1

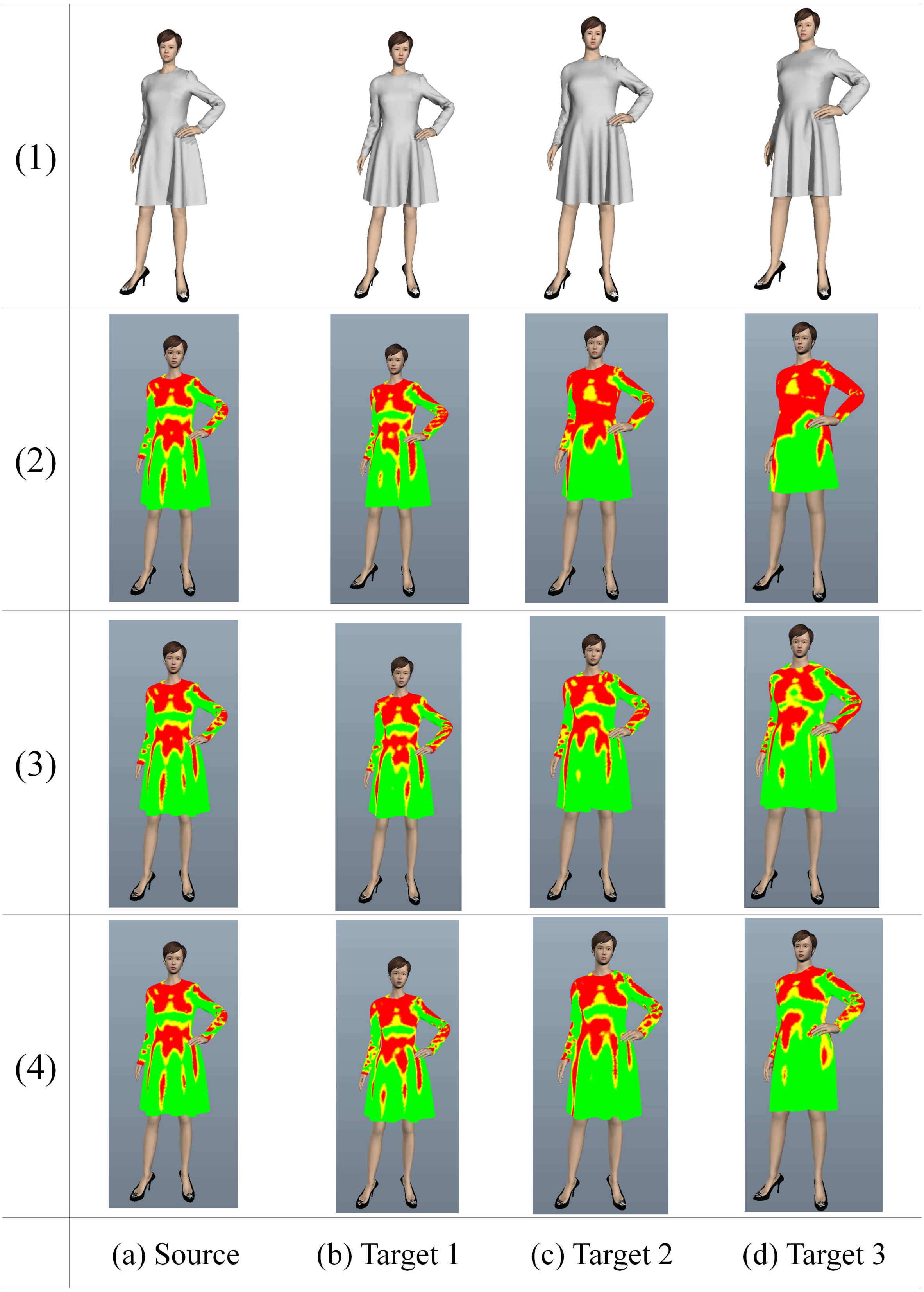

Figure 10: Result figures 2