Computer Technologies for Designing Close-Fitting Apparel with Specific Properties

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Abstract. In this study, based on the 3D scanning technology and virtual simulation, the digital twins of female bodies were adjusted and developed, and a virtual simulation of wetsuit was carried out. The virtual wetsuit was evaluated through the digital twin morphology, and the wetsuit sewing pattern block was optimized through composite material strain and compression value. The experimental tests show that the digital twins of system "body - wetsuit" based on real data transformation are feasible and practical, and the optimized pattern block guarantees good fit performance.

1 Introduction

At present, few kinds of research related to wetsuit design from South Korea, and the United States are involving together all aspects such as pattern design, material, simulation, etc. Choi\textsuperscript{1,2} made the study about pattern development, wetsuit production, and used a standard approach to make the pattern blocks with standing postures of the divers. Nagli\textsuperscript{3,4} and Avădanei\textsuperscript{5} scanned the bodies on the land in six postures, such as raising hands and squatting, and designed the virtual wetsuit with improved ergonomic characteristics.

Some research focused on the virtual design of compression clothing, Shimana et al.\textsuperscript{6} made research about garment construction for typical swimming posture with a special unilateral hand overhead. The study areas of virtual design included the original scanning, deformed and regenerated replicas.\textsuperscript{7} Danckaers\textsuperscript{8} and Cheng et al.\textsuperscript{9} established the correlation between virtual and real objects and provided the method to express the morphology characteristics of the human body after analyzing the changed multiple body parts. Mah\textsuperscript{10} developed 3D body construction based on human body "feature points". Ernst\textsuperscript{11} studied the compression deformation of soft tissue in the sagittal-plane of the female 3D model with much fat content. Besides, the female's chest size changes greatly, which also needs to be analyzed emphatically. Coltman et al.\textsuperscript{12} measured female breast volume change when standing with hands up and lying prone.

The way of digitizing physical objects through their digital replicas is a kind of reverse engineering. In this study, the real bodies are performed in virtual reality, multiple types of digital replicas based on morphological features of body deformation in dynamic are established and evaluated in the virtual system.

This study explores the wetsuit design process with the help of 3D scanning and simulation technologies depending on "digital twin" concept. It will help wetsuit designers
respond to rapid modification, evaluation, and omit actual repetitive manufacture works for optimizing pattern design, enhancing productivity, and further improving customer's wearing experience.

2 Experiments

2.1 Devices and Materials

VITUS Smart XXL 3D body scanner with the Anthroscan program was used to measure, read, and visualize the images of scanned bodies. CLO 5.0 virtual software was applied to change some basic body measurements and to do the simulation. 3ds Max was applied to modify human mesh cloud. SPSS was used to analyze the measurement results through correlation and regression analysis, reliability analysis, and normality test. KES-F system was used to test mechanical properties of material.

The commonly used composite material with thickness 3 mm was selected. The composition are: the inner layer and outer layer were made of polyester knitted fabric, the intermediate adhesive bonding layer was Styrene chloroprene rubber (30% chloroprene rubber + 70% styrene-butadiene rubber). The maximum elongation of the material is 30.17%, and the elongation of body skin under different postures are 12.8-17.5%.

2.2 Objects and body morphology

Wetsuit should keep warm underwater, so it needs to be tight fitting to prevent excess water from entering the suit. So wetsuit was chosen for this study as an example of close-fitting apparel with compression effect.

96 Asian female bodies with the heights 147.3-173.6 cm and the ages 18-27 were measured. All body measurements are following standard ISO 7250. Table 1 shows eight main body measurements for generating a digital twin.

<table>
<thead>
<tr>
<th>ID</th>
<th>Measurements interpretation</th>
<th>Symbols</th>
<th>Avg., S.D., cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Distance 7CV (BNP) to vertical</td>
<td>-</td>
<td>27.0 ± 1.8</td>
</tr>
<tr>
<td>2</td>
<td>Distance neck front (FNP) to vertical</td>
<td>-</td>
<td>36.6 ± 2.0</td>
</tr>
<tr>
<td>3</td>
<td>Distance waist to vertical</td>
<td>-</td>
<td>44.2 ± 3.0</td>
</tr>
<tr>
<td>4</td>
<td>Distance waist back to vertical</td>
<td>-</td>
<td>26.1 ± 2.9</td>
</tr>
<tr>
<td>5</td>
<td>Bust girth</td>
<td>BG</td>
<td>88.1 ± 8.0</td>
</tr>
<tr>
<td>6</td>
<td>Waist girth</td>
<td>WG</td>
<td>70.9 ± 8.5</td>
</tr>
<tr>
<td>7</td>
<td>Neck front (FNP) to waist</td>
<td>FNP-WL</td>
<td>32.8 ± 2.5</td>
</tr>
<tr>
<td>8</td>
<td>Neck back (BNP) to waist centre back</td>
<td>BNP-WL</td>
<td>37.1 ± 2.2</td>
</tr>
</tbody>
</table>

Figure 1 shows the representative dynamic diving postures. Figure 2 shows the structure of developed wetsuit patterns with compression ability.

2.3 Generating of digital twin in dynamic postures

Digitalized 3D female avatars as cloud mesh with the coordinates of the key feature points were obtained through the 3D scanner. The feature points on the bust and other parts of body were adjusted and deformed.
Figure 3 shows how the female torso changed under the influences of dynamic posture (raising arms).

**Figure 1.** Dynamic postures.

**Figure 2.** The designed wetsuit pattern.

**Figure 3.** Overlapped torso graphics in arms down (black) and up (green) (a), sagittal-plane (b).

Figure 3a shows the overlapped two torsos belonging to naturally standing postures: the black mesh when the arms down, the green mesh when the arms raising. The BP location...
has been modified in 3ds Max through editing it coordinates ($\Delta x$, $\Delta z$, and $\Delta y'$, unit: cm). The BP with initial coordinates (7.822, -15.014, 0.000) moved to BP’ new position with final coordinates (6.780, -13.347, 0.442) when $\Delta x' = -1.042$ cm, $\Delta y' = 1.667$ cm, and $\Delta z = 0.442$ cm. Moreover, the parallelepiped in x-y-z axes illustrates the moving track (red line) of BP in three-dimensional space.

Figure 3b shows the sagittal-plane of two postures overlapped in crotch point CR. In initial positions the centre lines of the torso marked in red: the front line – FNP to FWP (4050), the back line—BNP to BWP (5040). Besides, the blue points and lines illustrate the changing of the torso tilts backward after raising arms. The values of the deformed twin after raising arms are as follows: length 4050 increases a little (avg. 10.6%), FNP moves to FNP’ in $\Delta f$, FWP moves to FWP’ in $\Delta f$; length 5040 decreases a little (avg. -15.5%), BNP moves BNP’ in $\Delta b$ to, BWP to BWP’ moves in $\Delta b$.

3 Results and analysis

3.1 Objective evaluation

The objective evaluation was carried out through two measured factors—the virtual pressure and the material strain. The virtual pressure was measured with software CLO 3D, the strain with KES-F.

The pressure value is an important factor, the comfortable pressure in tight clothing is usually less than 3.92 kPa. During diving, the full pressure will increase by dynamic component which also needs to be kept in a certain range. Therefore, the fitness can be judged by comparing value $\Delta P$

$$\Delta P = \frac{100 \times (P_{au} - P_{ad})}{P_{ad}},$$

where are $\Delta P$ is a relative difference between the pressure measured in static and dynamic postures, %; $P_{au}$ is the virtual pressure when arms up, kPa; $P_{ad}$ is the virtual pressure value when arms down, kPa.

Besides, the virtual material strain should be checked whether it exceeds the reference value of material real mechanical elongation (KES), or the designed ease. However, the characteristics of multi-layer material in virtual system can not be fully simulated, so this index is only for reference.

Figure 4 shows the performance of scanned mesh model, digital twin, and real wetsuit in static and dynamic. The digital clone is the same as scanned bodies. Design ease of pattern blocks of several body parts were calculated according to the relationship between the body measurements in dynamic postures and the material properties. Then, the wetsuit try-on was evaluated by means of generated digital twin to check pressure comfort, the design ease allowances, and the line configuration of pattern block.

As can be seen from the pressure map, it has good performance (in line with the real) with the digital replica. The $\Delta P$ at the critical body parts (SP, BP, and side) are -17.3%, 1.3%, and 16.2% respectively.

In static, the average virtual $P_{ad}$ is 1.89 kPa, and real $P_{ad}$ is 1.65 kPa; In dynamic, the average virtual $P_{au}$ is 1.75 kPa, and real $P_{au}$ is 1.60 kPa.

The deviation between real and virtual is less than 0.24 kPa, it means the virtual and real compression have little difference. It can be concluded that the objective compression experience of the digital twin can be used to predict real pressure performance.

Moreover, through the measurement results of multiple girths, the material strain values are close to the range of 12.8-17.5% (the design ease), the maximum material strain is no more than 25%. So, the pressure value and material strain are reasonable.
This digital twin can adapt to the real human body shape in static and dynamic and can complete the design through virtual technology.

### 3.2 Virtual appearance criteria

The appearance fitness can be directly observed through the virtual try on in Figure 4. The wetsuits are well tight without folds.

### 3.3 Subjective evaluation

Figure 5 shows the results of subjective evaluation test Likert Scale 7-level.

Through the subjective evaluation, a very good result was obtained. The average rating is 6.7, and wearing satisfaction has been achieved in both static and dynamic—with very highly satisfied compression feeling, and can easily perform all kinds of movements in a large range.

### 4 Conclusion

Based on human body scanning data, the digital twin of system "wetsuit—female body" was created by 3D software in terms of the both deformation processes of bodies and composite materials. The digital twin was generated based on the measurements and characteristics of real human body in dynamic postures. The wetsuit design was completed and evaluated by virtual technologies with a reasonable pressure range and good fit performance.

The subjective evaluation in the real try on also achieved high satisfaction. It proves the accuracy of digital twin, and provides a scientific-based method for wetsuit design.
5 Acknowledgments

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References