3D Biodigital Design, Fabrication, and Biomechanical Visualization of Custom-Fit of Compression Stocking

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PolyU UoA 38
## 3D Biodigital Design, Fabrication, and Biomechanical Visualization of Custom-Fit of Compression Stocking

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Title: 3D Biodigital Design, Fabrication, and Biomechanical Visualization of Custom-Fit of Compression Stocking

Descriptor

Poor-fitting markedly hinders the use of compression stockings (CSs). Differences in morphology and leg dimensions among individuals induce variability in their pressure profiles. In Hong Kong, the major supply of CSs comes from the West. CSs produced by Western brands are not usually adapted to the average sizes of the local Asian population. The non-match coefficient is as high as 27%-41%, which is the foundation of the current study.

This research aimed to design and develop a user-oriented biodesign-fabrication-evaluation system to enhance pressure function and user fit. The system was created by combining 3D digital body scanning, magnetic resonance imaging, digital seamless knitting technology, biomechanical visualization, and product realization. The research objectives were as follows: (1) to formulate a new method based on 2D digital limb cross-section scanning that can predict the pressure exerted by CSs; (2) to develop 3D finite element (FE) models that can evaluate the skin pressure, tissue deformation, and internal stress of the lower limbs induced by CSs; (3) to establish a technique for 3D image digital data transfer to visualize the knitting effects of CSs; and (4) to develop “outfit” that satisfy end users according to the mutual agreement between the practical measurements and the developed FE model. This study attracted HK$3.5 M in funding from the Hong Kong Polytechnic University, the General Research Fund, and the Innovation Technology Fund from the Hong Kong SAR Government. The project received “Best Paper Award” and appeared in the 1st Global Artificial Intelligence Conference (2018). The project also resulted in the generation of eight papers, three patents, and over 300 pairs of new CSs. This research provided an evidence-based design approach for custom-fitted CSs offering improved fitting and comfort for practical use.
Dr. Rong Liu

Rong is a researcher and practitioner on biofunctional textiles and the design, development, technology, and commercialization of fashion products. With a focus on improving clinical treatment, user comfort, active performance, and the quality of healthcare, she has integrated multidisciplinary approaches including product design, material science, textile engineering, biomechanics, physiotherapy, and psychophysiological assessment to explore the potential of various biomedical materials and wearable modality design for compression therapy.

This study presents a new system (tool) for biodigital-based design, fabrication, and biomechanical visualization of functional compression textiles. This system enhances pressure design for a better fit, wearer comfort, and treatment efficacy in the use of custom-fitted CSs.
Research Output / Body of Work

- A biodigital design system (tool) of custom-fitted CSs.
- A 3D biomechanical visualization platform to intuitively display pressure/stress function of CSs.
- A set of rich database of digitalized Magnetic Resonance Images of human lower limbs' biostructures.
- A new skin pressure prediction technique based on 3D digital body scanning and 2D limb cross-sectional images.
- New compression textiles materials and custom-fitted CSs for different end-users.
- 8 publications in fields of textiles, healthcare, clinical medicine, ergonomics, and human factors.
- 3 patents on compression stockings fabrication methods.
- 1 Research Award at the 1st Global Artificial Intelligent Conference on Fashion and Textiles.
- 1 Product Development Award by a Hong Kong leading textile industry company.
- 3 new granted research projects based on the output.
- Newly-developed custom-fitted CSs for elderly people and nursing staff.
Design Innovation

- Created a new method to predict skin pressure by CSs using 2D digital limb cross sectional images.

- Developed a new digital technique to predict pressure dosage based on the lower limb geometries determined by 3D body scanning.

- Developed a digital data transfer technique from body scanning to digital knitting of CSs.

- Created 3D finite element models to visualize:
  - skin pressure profiles exerted by CSs
  - limb surface curvature variation
  - internal tissue stresses
  - pressure transmission within soft tissue induced by CSs

- Created custom-fitted CSs for individuals.

- Built up a biodigital “design–fabrication-evaluation” system for CSs.
Research Questions

The research sets out to explore:

• How to deliver controllable pressure dosages to the lower limbs with specific characteristics for improving compression therapy?

• How to effectively fabricate custom-fitted CSs to realize personalized pressure magnitudes and gradient distributions?

• How to predict and holistically visualize the biomechanical function of compression stocking on the individual body?

• How to buildup a digital-based “design-fabrication-evaluation” system to improve user fit and wearing comfort of CSs?
The research fields include:

(1) Anthropometric and morphological characterization of human lower limbs.

(2) Anatomy and biostructure segmentations of human lower limbs.

(3) Working mechanisms analysis on interactions of “clothing-human body-environment”.

(4) Elastic compression materials design and analysis.

(5) Advanced seamless knitting structural design and knitting technology.

(6) Biomedical magnetic resonance image scanning and analysis technology.

(7) Bio-structures extraction and 3D modeling of the lower limb (skin, muscle, bone, vein).

(8) 3D modeling of the functional garment based on size and material mechanical properties.

(9) Biomechanics analysis and finite element modeling.

(10) Custom-fitted compression stockings development.

(11) Wear trial and experimental validation.
Research Fields and Key Works Referenced

**Digital design in fashion & textile engineering**

Traditionally, in the fashion industry, the basic patterns are designed for bodices that comprise the dimensional typology model for a given population. The definition of the basic model or pattern follows the practical manufacturing of the product, a laborious process that involves high costs with respect to labor and raw materials.

As consumer behavior and demands rapidly change, small and customized clothing requires the actual design process to be adapted to the dynamic nature of markets and the requirements of potential users. In fashion design, especially for the virtual prototyping and quality evaluation tasks, the integration of physics-based models with a Computer-Aided Design system has led to highly accurate cloth shape results. However, the linking of digital human body data with digitalized fabrication and biofunctional virtualization remains a great challenge.

**3D modeling & numerical simulation in bioengineering**

The computational modeling of complex physiological systems and their interaction with medical devices have constituted a major area of bioengineering research globally.

For example, as an aid to the planning of surgical interventions, computational fluid dynamics have been used to simulate blood flow in arterial networks. The numerical simulation of bone remodeling has also provided a great opportunity for improving the choice of therapy for complex bone defects. Computer models of the human face can be used as a powerful tool in animation development applications. Moreover, 3D modeling and simulation provide quantitative and qualitative data for the development of safe and efficacious medical devices. Such data provide clinicians and researchers with insights into normal and abnormal physiological function. However, the application of 3D modeling technology in biocompression textiles and garments has been rarely reported in the literature.
Biofunctional Compression Textiles

Functional compression textiles have been widely applied in the fields of medicine, healthcare, sports, and personal protection. The global compression wear market is expected to grow at a compound average growth rate of 5.1% from 2017 to 2022\(^9\).

The global increase in chronic venous disorders (CVDs) and the growth of the fitness and sports industry are major factors increasing the potential of compression textiles. CSs, leggings, and bandages have become the mainstay in the management of lower limb heaviness, tiredness, discomfort, swelling, and venous diseases that are related to body posture, aging\(^10\), sports injury\(^11\), physiological variation\(^12\), and occupational stress\(^13\). In particular, CS, as an important prophylaxis and treatment approach, has become a widely used modality for treating CVDs through its pressure control from the distal to the proximal lower limb to counteract the gravity force, facilitating venous return\(^14\).

The resulting mechanical pressure is largely influenced by the force-elongation behavior of textile structures, geometric morphologies, and anatomic location to which it is applied. Numerous clinical studies have demonstrated the efficacy of CSs in reducing venous reflex, improving blood circulation, and promoting the reabsorption of interstitial fluid\(^15-17\). However, in practice, high noncompliance has affected compression efficiency and use frequency. A large-scale CVD investigation reported that 63% of 3144 patients did not use CSs due to noncompliance and the inapplicability of CSs\(^18\). The nonuse of CSs on a regular basis has led to the persistence or recurrence of symptoms. To improve user compliance, the initiation of a stocking fitting service was recommended by 77% of respondents\(^19\).
Research Fields and Key Works Referenced

Research Gap

- Personalized medicine has been highly demanded for customized compression therapy. However, most commercial CSs follow standardized size charts from manufacturers or brand-name companies, which commonly neglect the variability between individuals and between consumers in different geographic locations.

- In practical use, differences in body mass and dimensions between the users in East Asia and the West have resulted in the ill-fitting of CSs. Compared with the average man in East Asia, the average man in the United Kingdom is 10 cm taller and 31.7% heavier. Two individuals may have differently sized calves and thighs even if their ankle dimensions are the same.

- In existing methods of pressure evaluation using wooden lower limb models and limited individual pressure sensors (single and multiple) on specific sites of the body, holistic pressure profiles by CSs in a continuum plane are difficult to obtain, and the important information such as pressure transmission from the skin to the deeper tissue cannot be measured using the existing sensor technologies.

- New design and pressure evaluation strategies that improve fitting and the pressure function of CSs are in high demand.
Stage I: Digitalized body characterization: A visual approach
  - Task 1: 3D digital body scanning for determination of leg surface geometry and morphology
  - Task 2: Strategies of stocking pressure prediction using leg surface curvature and geometry
Stage II: 3D biodigital knitting design and fabrication approach
  - Task 1: Stocking size fitting design and digital knitting structural design
  - Task 2: Advanced 3D seamless digital knitting of custom-fit CS
Stage III: Finite element modelling of leg-compression stocking system
  - Task 1: Geometric reconstruction and finite element leg-stocking model
  - Task 2: Biomechanical visualization of CSs
Stage IV: Validation of 3D biodigital design and biomechanical visualization system
  - Task 1: Pressure assessment on end-user via wear trials
  - Task 2: The workflow of “design-fabrication-evaluation” system of CSs for the individual users
Stage V: Custom-fitted compression stocking development for end users
  - Task 1: Custom-fitted compression stocking development for individuals
  - Task 2: Users feedback analysis and follow-up
Research Methods and Materials

Stage I: Digitalized body characterization: A visual approach

- **Task 1**: 3D digital body scanning for determination of leg surface geometry and morphology.

  ![Digitalized body scanning](image)

(1) In traditional factory, rigid leg models with round circumferences were used in pressure quality control.

(2) However, human legs are highly diverse in cross-sectional shapes. Different cross-sectional curvatures result in varying skin pressures by CSs.

(3) Circular cross-section of leg model: generating homogeneous pressure.

(4) Real human leg’s irregular cross-section: generating heterogeneous pressure.

The current quality control method ignores leg irregularity of individuals, potentially resulting in ill-fitting and discomfort of CSs in use.
Research Methods and Materials

Stage I: Digitalized body characterization: A visual approach

- **Task 1:** 3D digital body scanning for determination of leg surface geometry and morphology.

  A VITUS Bodyscan scanner based on optical double triangulation was applied to produce non-contact and true-to-scale 3D lower limb measurement model.

  Eight sensor heads are set on the four columns around the tested subject in scanning booth, which generates a contact-free 3D recording of body measurements with a **fast scanning process** (12 sec.), and **high accuracy** (the average circumference error < 1 mm).

  No tape measurement is needed.
Research Methods and Materials

Stage I: Digitalized body characterization: A visual approach

- **Task 1**: 3D digital body scanning for determination of leg surface geometry and morphology.

A total of **1200** anatomic sites at the **300** leg cross-sectional slices were investigated through 3D digital body scanning.

Findings: cross-sectional curvatures are different at the same slice and along different heights.
Research Methods and Materials

Stage I: Digitalized body characterization: A visual approach

- **Task 1**: 3D digital body scanning for determination of leg surface geometry and morphology.

![Diagram](image)

Existing “standard size chart” only considers general leg changes but neglecting specific characteristics of individual lower limbs.

Unfitted CSs could produce reversed pressure profiles, causing side effects (or tourniquet effect), impeding venous return.

(a) Lower limbs with similar ankle sizes may have highly varying sizes at calf, knee and thigh.

(b) Lower limbs with similar shapes may produce highly differences in leg sizes.
Research Methods and Materials

Stage I: Digital characterization of lower limb on geometry and morphology

- **Task 2**: Strategy on stocking pressure prediction using leg surface curvature and geometry.

(a) Leg circumference variations before & after use CS

The intervention of CS significantly variates surface curvatures of the calf and thigh where elastic-soft tissue dominated zones.

(b) Quantitative relations between stocking size, leg size, fabric stretch (%), and tension forces (N).

This result contributes to stocking shape design and pressure prediction.
Research Methods and Materials

Stage I: Digital characterization of lower limb on geometry and morphology

- **Task 2**: Strategy on stocking pressure prediction using leg surface curvature and geometry.

Digitalized leg cross-sectional slices determined by 3D scanning for geometric characterization.

(a) Through setting a 2D coordinate system, the max. curvatures (Curvmax.) of the key anatomic sites (P1, P2, P3, P4) at anterior, posterior, lateral, and medial aspects around leg were determined.

(b) Using GetData Graph Digitizer, the simulated polynomial curving models of the lines where the key anatomic sites located can be determined.

(c) According to the “similarity principle”, the curvatures of the corresponding tangent points at the REAL biologic leg cross-section ($K_{0}$) can be calculated via an equation,

$$K_{0(p1,p2,p3,p4)} = \frac{tC \times K_{(p1,p2,p3,p4)}}{tC_{0}}$$
Stage I: Digital characterization of lower limb on geometry and morphology

- **Task 2**: Strategy on stocking pressure prediction using leg surface curvature and geometry.

<table>
<thead>
<tr>
<th>Cross sections</th>
<th>Directions</th>
<th>Curvatures without ECS (cm⁻¹) Mean ± SD†</th>
<th>Curvatures with ECS (cm⁻¹) Mean ± SD</th>
<th>Difference mean ± SD between with and without ECS</th>
<th>Paired-t test t-value</th>
<th>Sig.</th>
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</thead>
<tbody>
<tr>
<td>Ankle (B)</td>
<td>Posterior (BP1)</td>
<td>0.56 ± 0.18</td>
<td>0.53 ± 0.06</td>
<td>0.03 ± 0.14</td>
<td>0.617</td>
<td>0.557</td>
</tr>
<tr>
<td></td>
<td>Medial (BP2)</td>
<td>0.24 ± 0.04</td>
<td>0.25 ± 0.48</td>
<td>-0.01 ± 0.04</td>
<td>-0.878</td>
<td>0.409</td>
</tr>
<tr>
<td></td>
<td>Anterior (BP3)</td>
<td>0.39 ± 0.12</td>
<td>0.34 ± 0.05</td>
<td>0.05 ± 0.13</td>
<td>0.975</td>
<td>0.362</td>
</tr>
<tr>
<td></td>
<td>Lateral (BP4)</td>
<td>0.28 ± 0.07</td>
<td>0.25 ± 0.02</td>
<td>0.03 ± 0.06</td>
<td>1.357</td>
<td>0.217</td>
</tr>
<tr>
<td>Brachial (B1)</td>
<td>Posterior (B1P1)</td>
<td>0.28 ± 0.13</td>
<td>0.21 ± 0.02</td>
<td>0.07 ± 0.13</td>
<td>1.594</td>
<td>0.155</td>
</tr>
<tr>
<td></td>
<td>Medial (B1P2)</td>
<td>0.29 ± 0.08</td>
<td>0.23 ± 0.06</td>
<td>0.06 ± 0.08</td>
<td>2.159</td>
<td>0.068</td>
</tr>
<tr>
<td></td>
<td><strong>Anterior (B1P3)</strong></td>
<td><strong>0.31 ± 0.06</strong></td>
<td><strong>0.23 ± 0.04</strong></td>
<td><strong>0.07 ± 0.07</strong></td>
<td><strong>2.753</strong></td>
<td><strong>0.028</strong></td>
</tr>
<tr>
<td></td>
<td>Lateral (B1P4)</td>
<td>0.21 ± 0.05</td>
<td>0.19 ± 0.03</td>
<td>0.02 ± 0.07</td>
<td>0.762</td>
<td>0.471</td>
</tr>
<tr>
<td>Calf (C)</td>
<td>Posterior (CP1)</td>
<td>0.17 ± 0.02</td>
<td>0.18 ± 0.03</td>
<td>-0.01 ± 0.04</td>
<td>-0.642</td>
<td>0.542</td>
</tr>
<tr>
<td></td>
<td>Medial (CP2)</td>
<td>0.26 ± 0.07</td>
<td>0.23 ± 0.03</td>
<td>0.03 ± 0.06</td>
<td>1.517</td>
<td>0.173</td>
</tr>
<tr>
<td></td>
<td><strong>Anterior (CP3)</strong></td>
<td><strong>0.30 ± 0.04</strong></td>
<td><strong>0.24 ± 0.04</strong></td>
<td><strong>0.06 ± 0.05</strong></td>
<td><strong>3.156</strong></td>
<td><strong>0.016</strong></td>
</tr>
<tr>
<td></td>
<td>Lateral (CP4)</td>
<td>0.16 ± 0.03</td>
<td>0.17 ± 0.02</td>
<td>-0.01 ± 0.03</td>
<td>-0.493</td>
<td>0.637</td>
</tr>
<tr>
<td>Knee (E)</td>
<td>Posterior (EP1)</td>
<td>0.18 ± 0.07</td>
<td>0.19 ± 0.08</td>
<td>-0.01 ± 0.10</td>
<td>-0.321</td>
<td>0.758</td>
</tr>
<tr>
<td></td>
<td>Medial (EP2)</td>
<td>0.29 ± 0.17</td>
<td>0.26 ± 0.09</td>
<td>0.03 ± 0.15</td>
<td>0.498</td>
<td>0.634</td>
</tr>
<tr>
<td></td>
<td>Anterior (EP3)</td>
<td>0.21 ± 0.10</td>
<td>0.28 ± 0.05</td>
<td>-0.06 ± 0.11</td>
<td>-1.629</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Lateral (EP4)</td>
<td>0.20 ± 0.07</td>
<td>0.22 ± 0.05</td>
<td>-0.03 ± 0.09</td>
<td>-0.754</td>
<td>0.475</td>
</tr>
<tr>
<td>Thigh (F)</td>
<td>Posterior (FP1)</td>
<td>0.15 ± 0.04</td>
<td>0.18 ± 0.03</td>
<td>-0.03 ± 0.04</td>
<td>-1.839</td>
<td>0.109</td>
</tr>
<tr>
<td></td>
<td><strong>Medial (FP2)</strong></td>
<td><strong>0.17 ± 0.05</strong></td>
<td><strong>0.12 ± 0.02</strong></td>
<td><strong>0.05 ± 0.048</strong></td>
<td><strong>2.624</strong></td>
<td><strong>0.034</strong></td>
</tr>
<tr>
<td></td>
<td>Anterior (FP3)</td>
<td>0.15 ± 0.02</td>
<td>0.13 ± 0.02</td>
<td>0.02 ± 0.03</td>
<td>1.305</td>
<td>0.233</td>
</tr>
<tr>
<td></td>
<td>Lateral (FP4)</td>
<td>0.14 ± 0.03</td>
<td>0.14 ± 0.20</td>
<td>-0.00 ± 0.03</td>
<td>-0.213</td>
<td>0.838</td>
</tr>
</tbody>
</table>

* †p < 0.05; **p < 0.005; ***p < 0.001; †Standard deviation.

This design tool can illustrate the digitalized surface curvatures and variations at different heights and directions of the lower limbs for skin pressure prediction.
Research Methods and Materials

Stage I: Digital characterization of lower limb on geometry and morphology

- **Task 2**: Strategy on stocking pressure prediction using leg surface curvature and geometry.

Applying the developed algorithms, skin pressure exerted by CSs made of different fabric materials can be predicted based on the digitalized leg geometric features (e.g., circumference and curvatures).

### Circumference of leg:

\[
tC \approx \sqrt{\sum_{i=1}^{n} (x_{i+1} - x_i)^2 + (x_n - x_1)^2}
\]

### Curvature of radius (\(RoCo\)):

\[
RoC_{0(p1,p2,p3,p4)} = \frac{tC_0}{tC \times K_{(p1,p2,p3,p4)}}
\]

Predicted skin pressure (\(P_{skin}\)) induced by CSs at specific region (e.g., ankle, calf, knee or thigh):

\[
P_{skin}(mmHg) = \frac{2\pi \times T(N) \times n \times 75}{2\pi \times RoC_{0,mean}(cm) \times W(cm)} - \frac{T(N) \times n \times 471}{tC_{0,mean}(cm) \times W(cm)}
\]

(a) Instron (4411) tensile testing provide the required parameter values in the formula \(P_{skin}(mmHg)\): i.e., T-tension & W-width
Research Methods and Materials

Stage I: Digital characterization of lower limb on geometry and morphology

- **Task 2**: Strategy on stocking pressure prediction using leg surface curvature and geometry.

The experimental test was designed to validate the applicability of the developed algorithms.

(a) Pressure sensor set at a leg site, covering at least 3 cross-sectional slices with different surface curvatures and radius of curvatures for skin pressure detection.

(b) PricoPress pneumatic pressure sensor, a circular air-filled pressure sensor, measuring 5 cm in diameter, was used to test practical skin pressure at the 20 anatomic sites (4 directions X 5 heights) with max. surface curvatures of leg:

- Four directions: anterior, posterior, lateral, medial
- Five heights: ankle, brachial, calf, knee, thigh
Research Methods and Materials

Stage I: Digital characterization of lower limb on geometry and morphology

- **Task 2**: Strategy on stocking pressure prediction using leg surface curvature and geometry.

The design tool demonstrated a consistent varying trend between the measured and the predicted “skin pressures” along the key height levels, especially at the brachial (B1) and the thigh (F).

The results indicate that the developed digital method can be used as a simple but effective tool to predict stocking pressure based on the digitalized cross-sectional images extracted from 3D body scanning.
Stage I: Digital characterization of lower limb on geometry and morphology

- **Task 2:** Strategy on stocking pressure prediction using leg surface curvature and geometry.

Output: an effective approach was developed to predict skin pressure induced by CSs based on 3D body scanning images.
Research Methods and Materials

Stage II: Digitalized design and fabrication of custom-fitted compression stocking

- **Task 1**: 3D digital CSs fitting design and knitting structural design
Research Methods and Materials

Stage II: Digitalized design and fabrication of custom-fitted compression stocking

- **Task 2**: Advanced 3D seamless digital knitting of custom-fitted stocking

Programmable circular knitting based on the parametric structural design.

Microscopic structure analysis and tension test

Mechanical (tension) properties of the designed laid-in fabrics.
Research Methods and Materials

Stage II: Digitalized design and fabrication of custom-fitted compression stocking

• **Task 2**: Advanced 3D seamless digital knitting of custom-fitted stocking

1. A patented pressure design and fabrication technology of CSs.
2. The designed knitting recipes for different pressure zones of CSs for pressure control.
3. CSs testing in vivo and in vitro.
Research Methods and Materials

Stage III: Finite element leg-compression stocking model

- **Task 1:** Leg-stocking geometrics reconstruction.
Research Methods and Materials

Stage III: Finite element leg-compression stocking model

- **Task 2**: Biomechanical visualization of the designed CSs.

Longitudinal view: the 3D biodigital design system demonstrated that the designed CSs presented the highest pressure at the ankle and gradually decreasing up to the knee, delivering a controlled gradient pressure dosages to the lower limb.
Research Methods and Materials

Stage III: Finite element leg-compression stocking model

- **Task 2**: Biomechanical visualization of the designed CSs.

<table>
<thead>
<tr>
<th>Pressure Classes</th>
<th>Gradient levels</th>
<th>( W^* (\text{mm}^2) )</th>
<th>( E_1 (\text{MPa}) )</th>
<th>( E_2 (\text{MPa}) )</th>
<th>( G_{12} (\text{MPa}) )</th>
<th>( V )</th>
<th>( T (\text{mm}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I) Mild pressure</td>
<td>Ankle-B</td>
<td>3.25 ± 0.12</td>
<td>0.28 ± 0.02</td>
<td>0.19 ± 0.02</td>
<td>0.11 ± 0.01</td>
<td>0.27 ± 0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brachial-B1</td>
<td>2.75 ± 0.11</td>
<td>0.21 ± 0.02</td>
<td>0.15 ± 0.01</td>
<td>0.08 ± 0.01</td>
<td>0.33 ± 0.03</td>
<td>1.0 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>calf C</td>
<td>2.30 ± 0.10</td>
<td>0.16 ± 0.01</td>
<td>0.10 ± 0.01</td>
<td>0.06 ± 0.01</td>
<td>0.37 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>(II) Moderate pressure</td>
<td>Ankle-B</td>
<td>3.57 ± 0.13</td>
<td>0.36 ± 0.02</td>
<td>0.21 ± 0.02</td>
<td>0.14 ± 0.01</td>
<td>0.26 ± 0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brachial-B1</td>
<td>3.02 ± 0.13</td>
<td>0.27 ± 0.03</td>
<td>0.15 ± 0.01</td>
<td>0.11 ± 0.01</td>
<td>0.27 ± 0.02</td>
<td>1.1 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>calf C</td>
<td>2.53 ± 0.11</td>
<td>0.19 ± 0.01</td>
<td>0.09 ± 0.01</td>
<td>0.07 ± 0.01</td>
<td>0.29 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>(III) Strong pressure</td>
<td>Ankle-B</td>
<td>3.74 ± 0.14</td>
<td>0.41 ± 0.03</td>
<td>0.17 ± 0.02</td>
<td>0.17 ± 0.01</td>
<td>0.23 ± 0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brachial-B1</td>
<td>3.16 ± 0.13</td>
<td>0.32 ± 0.03</td>
<td>0.13 ± 0.01</td>
<td>0.13 ± 0.01</td>
<td>0.25 ± 0.02</td>
<td>1.2 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>calf C</td>
<td>2.65 ± 0.11</td>
<td>0.22 ± 0.02</td>
<td>0.08 ± 0.01</td>
<td>0.08 ± 0.01</td>
<td>0.27 ± 0.01</td>
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</tbody>
</table>

Longitudinal biomechanical visualization of multi-class (I, II, III) CSs pressure
Research Methods and Materials

Stage III: Finite element leg-compression stocking model

- **Task 2**: Biomechanical visualization of the designed CSs.

Digitalized skin pressure profiles at four directions around leg when being treated with 3 pressure classes (I, II, III) of CSs.
Research Methods and Materials

Stage III: Finite element leg-compression stocking model

- **Task 2**: Biomechanical visualization of the designed CSs.
Research Methods and Materials

Stage III: Finite element modeling (FEM) of leg-compression stocking system

- **Task 2**: Biomechanical visualization of leg-stocking design system.

Output

Biomechanical visualization: cross-sectional surface curvature variations before & after use of CSs

Skin surface curvatures
Research Methods and Materials

Stage IV: Validation of 3D biodigital design, fabrication, and biomechanical visualization system

- **Task 1**: Pressure profile assessment on end users in wear trial.

**New design tool—a digitalized leg-stocking model visualizing internal stress and external skin pressure induced by compression stocking**

The developed biodigital design and biomechanical visualization system demonstrated the capability on compression stocking design and pressure functional assessment & prediction.
Research Methods and Materials

Stage IV: Validation of 3D biodigital design, fabrication, and biomechanical visualization system

- **Task 2**: The workflow of 3D biodigital “design-fabrication-evaluation” system of compression stockings for individual customers.

Output: A biodigital design tool (system) has been developed for custom-fitted compression stocking

- Upgrade pressure design efficiency & pressure function
- Improve user fitting & comfort of compression stocking
Stage V: Custom-fitted compression stocking development for end users.

- **Task 1: Custom-fitted compression stocking development.**

300+ pairs of the new CSs have been developed and benefited the users from Tung Wah Group of Hospitals (TWGHs) including,

- Wong Chi Tong Day Care Centre for the elderly
- Wong Cho Tong Care and Attention home
- Wong Cho Tong Integrated Vocational Rehabilitation Centre Cum Hostel
- Enhanced Home and Community Care Services.

TWGHs is the largest charitable organisation with the longest history in Hong Kong. For over a hundred years, TWGHs’ medical and health, education and community services have developed rapidly to fulfil the needs of the society and to provide high quality services at low rates or for free.

Today, TWGHs operates 339 services centres, including 5 hospitals and 34 Chinese and Western medicine services centres, 57 education services centres, 241 community services centres that cover elderly, youth and family, rehabilitation and traditional services, as well as the Tung Wah Museum and TWGHs Maisy Ho Archives and Relics Centre, which were established to promote, restore and preserve the heritage and relics of TWGHs, with an aim to protect and preserve local traditional culture.
Research Methods and Materials

Stage V: Custom-fitted compression stocking development for end users.

Task 2: User feedback analysis and follow-up.

The developed CSs received positive comments and feedback from the end-users.

Ms. WY Cheung (52 yrs old): “I ever bought market compression stocking, but this stocking is more comfort and fitting, I satisfied it”.

Ms. NM Yeung (50 yrs old): “In general, the stocking feels fit, comfort and light in leg”.

Ms. YK Chiu (51 yrs old): “This stocking is easier to take on, easier move in walking, fit and comfort.”

Ms. D Wong (36 yrs old): “I felt leg lighter, easier walk, and comfort pressure”.

Ms SP Ko (55 yrs old): “This stocking is easier to take on and off, reduce leg fatigue feeling, skin contact is comfort, color is good”.

Ms Y Yiu (61 yrs old): “This stocking reduced my leg fatigue feeling, fit, and no discomfort perception”...
Research Conclusions

- In this project, a user-oriented biodesign-fabrication-evaluation system (tool) was developed to digitally design, realize, and holistically visualize the biomechanical functions of the designed custom-fitted CSs for individual users.

- By combing 3D digital body scanning, digital seamless knitting, and biomechanical visualization, this research work achieved the following objectives:
  
  (1) created a new method to predict the skin pressure applied by CSs by using 2D digital limb cross-sectional images;
  (2) built advanced 3D FE models to visualize the pressure, stress, curvatures, and deformations induced by CSs;
  (3) established a digital data transfer technique from 3D body scanning to the digital knitting of CSs; and
  (4) developed custom-fitted CSs to meet end-users’ requirements regarding specific leg shapes and dimensions.

- The developed 3D biodesign-fabrication-evaluation system (tool) can be applied in pressure prediction, functional analysis, and product development. The developed tool and designed custom-fitted CS products have benefited end-users, including elderly people and nursing staff in their daily lives.
Dissemination and distribution of outcomes

8 publications, 3 patents, 1 research award, 1 product development award, 3 new granted research projects, 300+ developed new compression stockings

Publication (8)


Dissemination and distribution of outcomes

8 publications, 3 patents, 1 research award, 1 product development award, 3 new granted research projects, 300+ developed custom-fit compression stockings

Publication (8)


Dissemination and distribution of outcomes

Invited Speaker (3)


Dissemination and distribution of outcomes

Patents (3)

1. **2014**  

2. **2016**  

3. **2016**  
Dissemination and distribution of outcomes

Awards (2)

<table>
<thead>
<tr>
<th>Year</th>
<th>Events</th>
</tr>
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<tbody>
<tr>
<td>2017</td>
<td>“Innovation &amp; Product Development Award” (R LIU) by Hong Kong Textile Leading Industry for the developed “Modern Integrated Compression Orthesis”, 5th Dec. 2017, Hong Kong.</td>
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</table>
Dissemination and distribution of outcomes

Commercialization

<table>
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<th>Year</th>
<th>Events</th>
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<tr>
<td>2017-2019</td>
<td>Industrial companies (e.g., Health Pathways Group) commercialized the developed compression stockings.</td>
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Newly granted research projects supporting PhD student and research staff for sustained studies

2017-2019  This research work attracted 3 new funded projects and research positions, including


- Block Research Grant (1-ZVLQ) (Principle Investigator) “3D Biodigital Design and Numerical Modelling for Biomedical Functional Textiles” (2017-2019), supported 3 Research Staffs in 2-year research work.

- Central Research Grant (G-YBUY) (Principle Investigator) “Biomechanical Study of Heterogeneous Compression Materials Using Finite Element Model” (2017-2019), supported 2 Research Staffs in 2-year research work.
References

References