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

Dr. Rong Liu

PolyU UoA 38

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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.

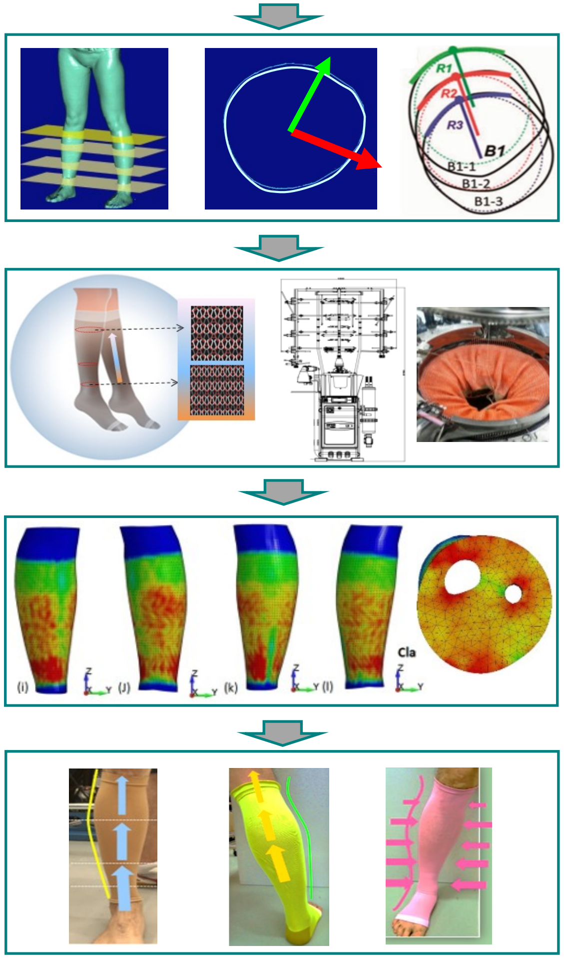
Research Output / Body of Work

- 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.

Research Output / Body of Work

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?

Research Fields and Key Works Referenced

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[1].

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[2] has led to highly accurate cloth shape results[2,3]. However, the linking of digital human body data with digitalized fabrication and biofunctional virtualization remains a great challenge[4].

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[5].

For example, as an aid to the planning of surgical interventions, computational fluid dynamics have been used to simulate blood flow in arterial networks[6]. The numerical simulation of bone remodeling has also provided a great opportunity for improving the choice of therapy for complex bone defects[7]. Computer models of the human face can be used as a powerful tool in animation development applications[8]. 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.

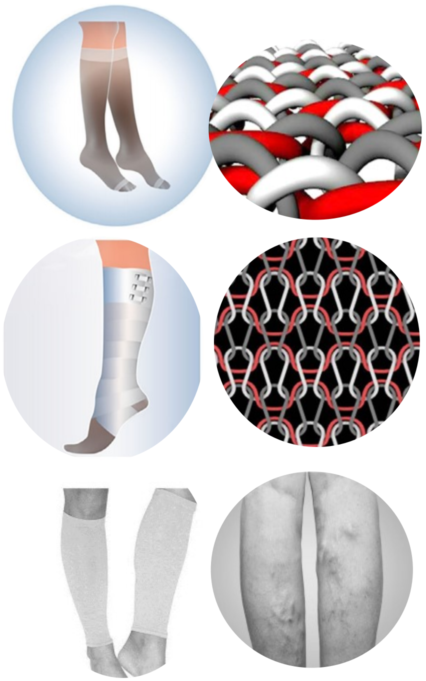
Research Fields and Key Works Referenced

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.

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
- 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

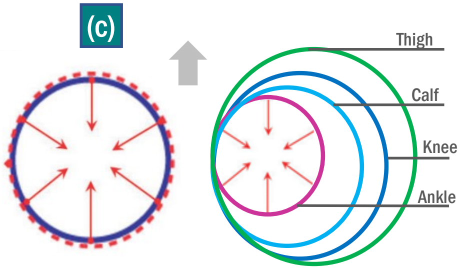
- Task 1: 3D digital body scanning for determination of leg surface geometry and morphology.

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

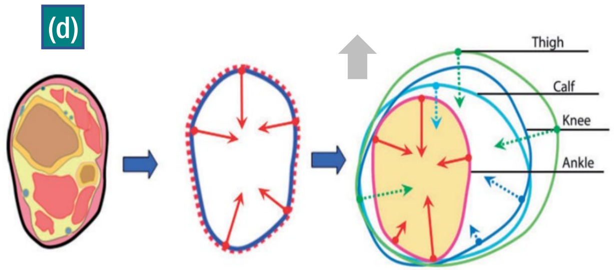
(2) However, human legs are highly diverse in cross-sectional shapes. Different cross-sectional curvatures result in varying skin pressures by CSs.

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

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



Homogeneous



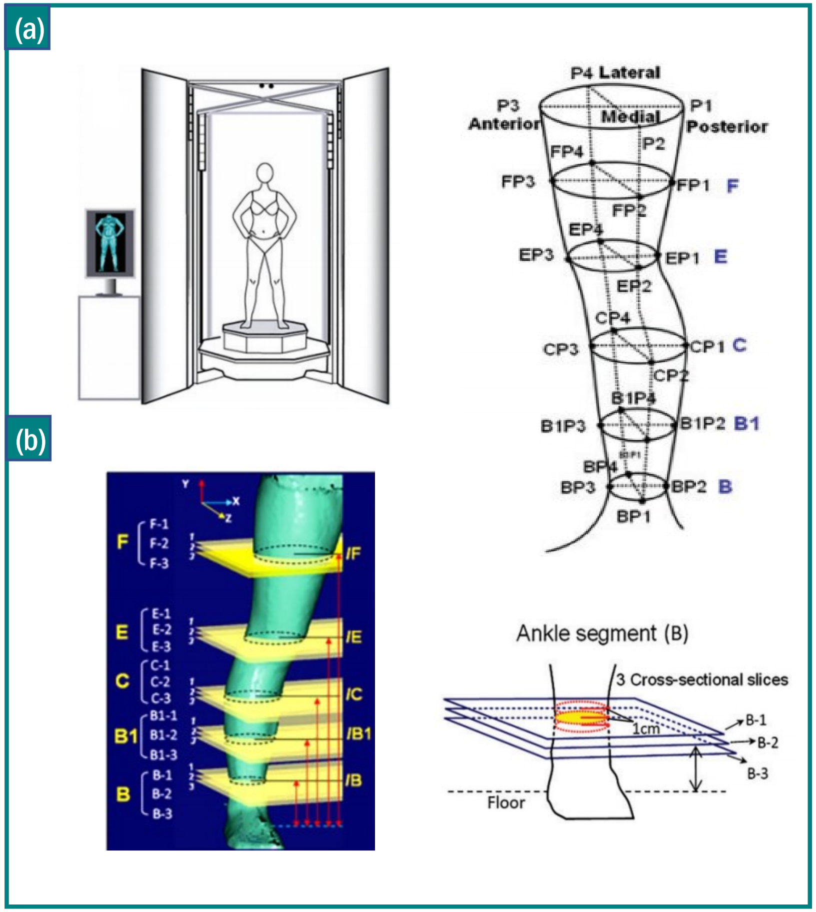
Heterogeneous

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.

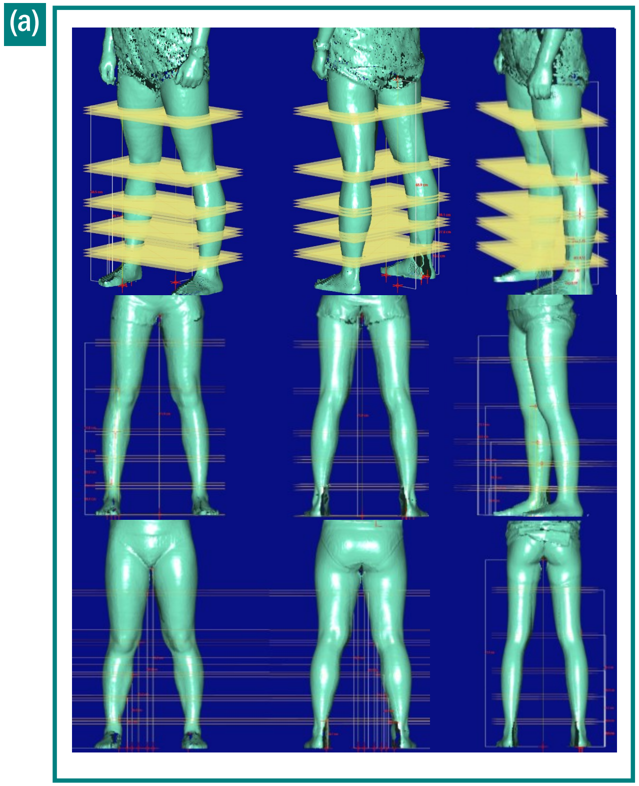
Eight sensor heads are set on the four columns around the tested subject in scanning booth, which generates a contact-free 3D recording of body measurements with a fast scanning process (12 sec.), and high accuracy (the average circumference error < 1 mm).

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.

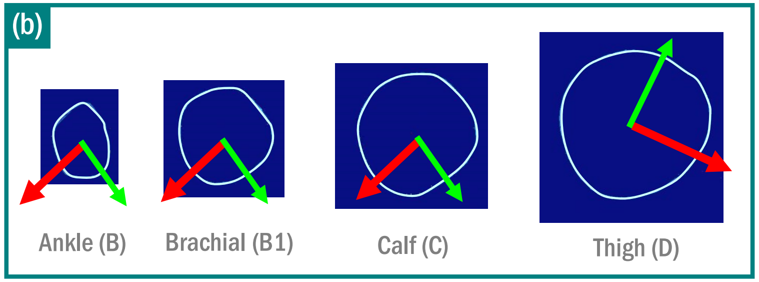


A total of 1200 anatomic sites at the 300 leg cross-sectional slices were investigated through 3D digital body scanning.

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

(a) Profiles of the longitudinal shape along the lower limb

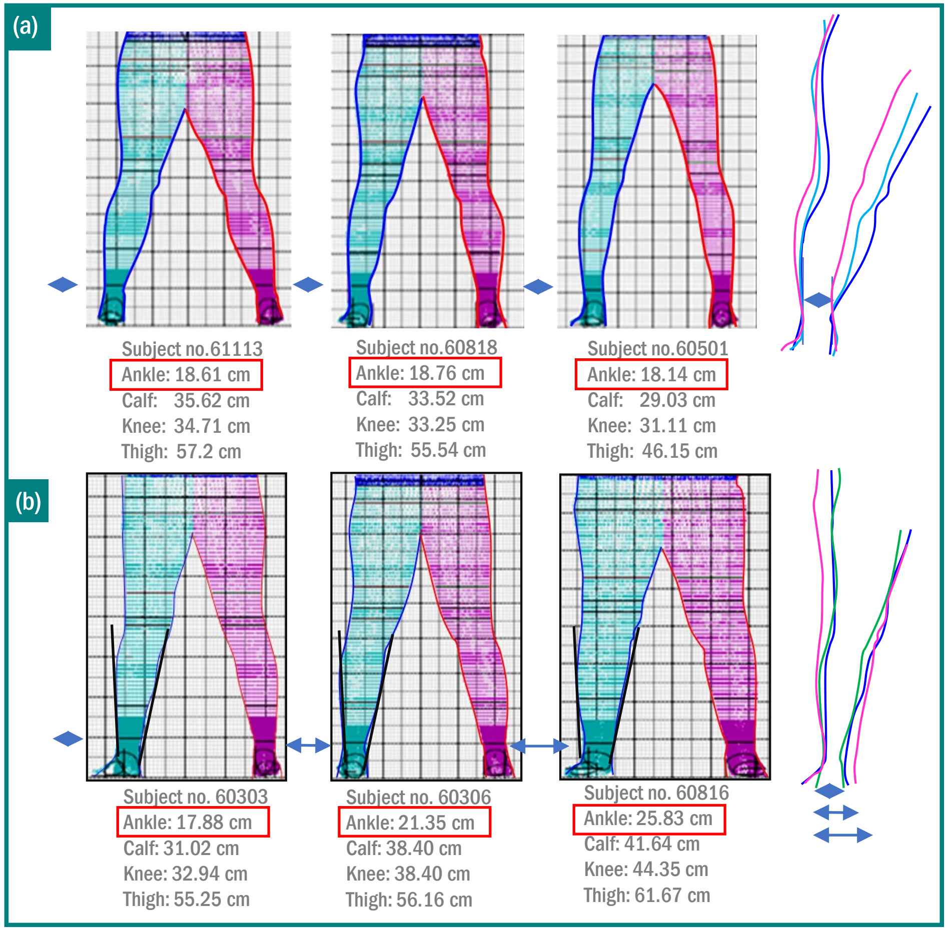
(b) Profiles of the cross-sectional slices along the lower limb



Research Methods and Materials

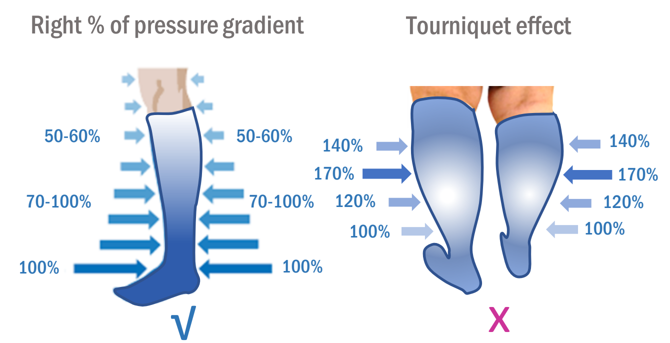
Stage I: Digitalized body characterization: A visual approach

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



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)

	Without ECS (cm)		With ECS (cm)		Comparison between with and without ECS		
Cross sections	Mean ± SD†	Variance	Mean ± SD	Variance	Difference mean ± SD	t-value	*Sig.*
Ankle (B)	21.34 ± 1.08	1.16	21.08 ± 1.04	1.11	0.25 ± 0.20	3.489	0.010*
Brachial (B1)	28.10 ± 1.41	1.99	27.91 ± 1.38	1.98	0.19 ± 0.17	3.146	0.016*
Calf (C)	34.98 ± 2.28	5.19	34.73 ± 2.19	4.93	0.24 ± 0.11	6.340	**0.000*****
Knee (E)	35.29 ± 1.84	3.37	34.77 ± 1.79	3.30	0.52 ± 0.41	3.576	0.009*
Thigh (F)	47.99 ± 3.52	12.37	47.33 ± 3.34	11.49	0.66 ± 0.46	3.7840	**0.007***

*$p < 0.05$; **$p < 0.005$; ***$p < 0.001$; †Standard deviation. ECS: elastic compression stockings

(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)

Cross-sections	Girth of CS (cm)	Girth of leg (cm)	Height (cm)*	Fabric stretch (%)	Fabric tension (N)
With ECS condition (mean ± SD†)					
Ankle (B)	16.00 ± 0.45	21.08 ± 1.04	10.64 ± 0.34	31.80 ± 6.49	4.90 ± 0.65
Brachial (B1)	20.40 ± 0.42	27.91 ± 1.38	19.71 ± 0.74	36.79 ± 6.78	4.42 ± 0.53
Calf (C)	22.00 ± 0.40	34.73 ± 2.19	28.97 ± 1.53	57.87 ± 9.94	6.36 ± 0.93
Knee (E)	21.00 ± 0.55	34.77 ± 1.79	42.73 ± 2.87	65.56 ± 8.51	6.75 ± 0.48
Thigh (F)	30.20 ± 0.65	47.33 ± 3.34	61.25 ± 3.11	56.73 ± 11.05	5.42 ± 0.89

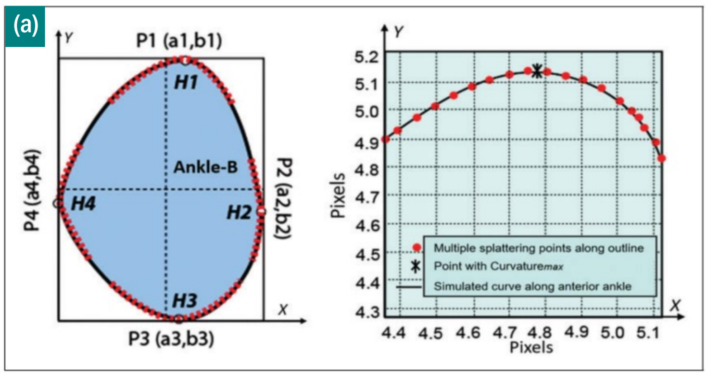
(b) Quantitative relations between stocking size, leg size, fabric stretch (%), and tension forces (N).

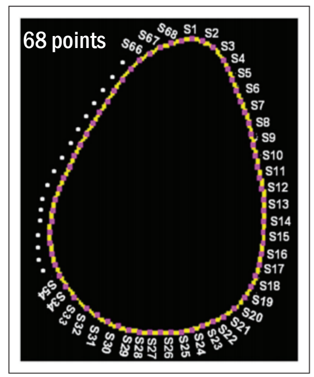
This result contributes to stocking shape design and pressure prediction.

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.





(b)

Segmental Lines	Simulated polynomial curving models	Adjusted R^{2*}
H1 (Anterior)	$Y = 735.9x^9 - 31122.0\,x^8 + (5.846\,e+5)\,x^7 - (6.401e+6)\,x^6 + (4.504\,e+7)\,x^5 - (2.111\,e+8)\,x^4 + (6.594\,e+8)\,x^3 - (1.323\,e+9)\,x^2 + (1.548\,e+9)x - 8.045e+8$	0.9985
H2 (Lateral)	$X = 62.4y^9 - 2270.0y^8 + 36666.0y^7 - (3.448\,e+5)\,y^6 + (2.082\,e+6)\,y^5 - (8.37\,e+6)\,y^4 + (2.24\,e+7)y^3 - (3.85\,e+7)\,y^2 + (3.853\,e+7)\,y - 1.712\,(e+7)$	0.9994
H3 (Posterior)	$Y = 7.849x^9 - 306.9x^8 + 5302.0x^7 - 53122.0x^6 + (3.397\,e+5)\,x^5 - (1.437\,e+6)\,x^4 + (4.012\,e+6)\,x^3 - (7.124\,e+6)\,x^2 + (7.279\,e+6)\,x - (3.25\,e+6)$	0.9991
H4 (Medial)	$X = 23.59\,y^8 - 798.0\,y^7 + 11800.0\,y^6 - 99588.0\,y^5 + (5.247e+5)\,y^4 - (1.768\,e+6)\,y^3 + (3.718\,e+6)\,y^2 - (4.464\,e+6)\,y + (2.342\,e+6)$	0.9989

*The adjusted R^2 was employed as a corrected goodness of fit (model accuracy) measure for the simulated curve models, in which the highest adjusted R^2 was considered to be the optimum one for precisely determining curvature properties of the tangent points along leg cross-sectional outline. The closer the R^2 was 1, the higher the degree of the simulated curve.

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

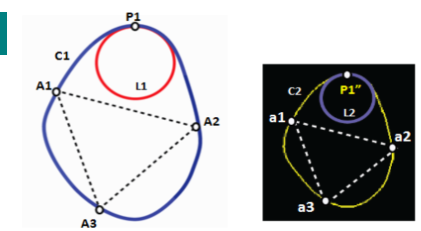
(a) Through setting a 2D coordinate system, the max. curvatures (Curvmax.) of the key anatomic sites (P1, P2, P3, P4) at anterior, posterior, lateral, and medial aspects around leg were determined.

(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 (*K0*) can be calculated via an equation,

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

(c)



Real leg cross section

Scanned leg cross-section

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.

Cross sections	Directions	Curvatures without ECS (cm^{-1}) Mean ± SD†	Curvatures with ECS (cm^{-1}) Mean ± SD	Difference mean ± SD between with and without ECS	Paired-t test	
					t-value	Sig.
Ankle (B)	Posterior (BP1)	0.56 ± 0.18	0.53 ± 0.06	0.03 ± 0.14	0.617	0.557
	Medial (BP2)	0.24 ± 0.04	0.25 ± 0.48	−0.01 ± 0.04	−0.878	0.409
	Anterior (BP3)	0.39 ± 0.12	0.34 ± 0.05	0.05 ± 0.13	0.975	0.362
	Lateral (BP4)	0.28 ± 0.07	0.25 ± 0.02	0.03 ± 0.06	1.357	0.217
Brachial (B1)	Posterior (B1P1)	0.28 ± 0.13	0.21 ± 0.02	0.08 ± 0.13	1.594	0.155
	Medial (B1P2)	0.29 ± 0.08	0.23 ± 0.06	0.06 ± 0.08	2.159	0.068
	Anterior (B1P3)	**0.31 ± 0.06**	**0.23 ± 0.04**	**0.07 ± 0.07**	**2.753**	**0.028***
	Lateral (B1P4)	0.21 ± 0.05	0.19 ± 0.03	0.02 ± 0.07	0.762	0.471
Calf (C)	Posterior (CP1)	0.17 ± 0.02	0.18 ± 0.03	−0.01 ± 0.04	−0.642	0.542
	Medial (CP2)	0.26 ± 0.07	0.23 ± 0.03	0.03 ± 0.06	1.517	0.173
	Anterior (CP3)	**0.30 ± 0.04**	**0.24 ± 0.04**	**0.06 ± 0.05**	**3.156**	**0.016***
	Lateral (CP4)	0.16 ± 0.03	0.17 ± 0.02	−0.01 ± 0.03	−0.493	0.637
Knee (E)	Posterior (EP1)	0.18 ± 0.07	0.19 ± 0.08	− 0.01 ± 0.10	−0.321	0.758
	Medial (EP2)	0.29 ± 0.17	0.26 ± 0.09	0.03 ± 0.15	0.498	0.634
	Anterior (EP3)	0.21 ± 0.10	0.28 ± 0.05	−0.06 ± 0.11	−1.629	0
	Lateral (EP4)	0.20 ± 0.07	0.22 ± 0.05	− 0.03 ± 0.09	−0.754	0.475
Thigh (F)	Posterior (FP1)	0.15 ± 0.04	0.18 ± 0.03	−0.03 ± 0.04	−1.839	0.109
	Medial (FP2)	**0.17 ± 0.05**	**0.12 ± 0.02**	**0.05 ± 0.048**	**2.624**	**0.034***
	Anterior (FP3)	0.15 ± 0.02	0.13 ± 0.02	0.02 ± 0.03	1.305	0.233
	Lateral (FP4)	0.14 ± 0.03	0.14 ± 0.20	−0.00 ± 0.03	−0.213	0.838

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

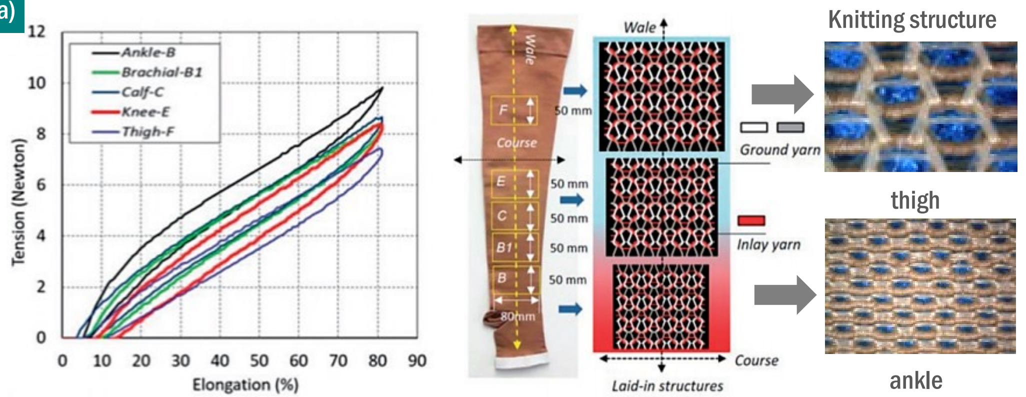
This design tool can illustrate the digitalized surface curvatures and variations at different heights and directions of the lower limbs for skin pressure prediction.

Research Methods and Materials

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

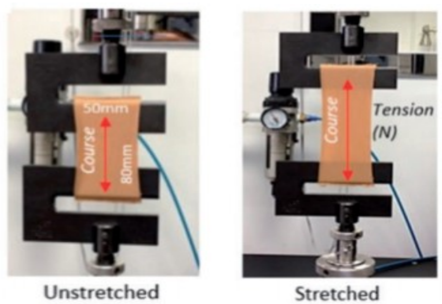
- Task 2: Strategy on stocking pressure prediction using leg surface curvature and geometry.

(a)



Basic characteristics of ECS sample

Height levels	Densities (stitches/inch²)	Thickness (mm)	Width (mm)
B	3,689	0.79	80
B1	3,135	0.77	102
C	2,844	0.77	110
E	2,419	0.75	112
F	1,935	0.73	151



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:

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

Curvature of radius (*RoCo*):

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

Predicted skin pressure (*Pskin*) induced by CSs at specific region (e.g. ankle, calf, knee or thigh):

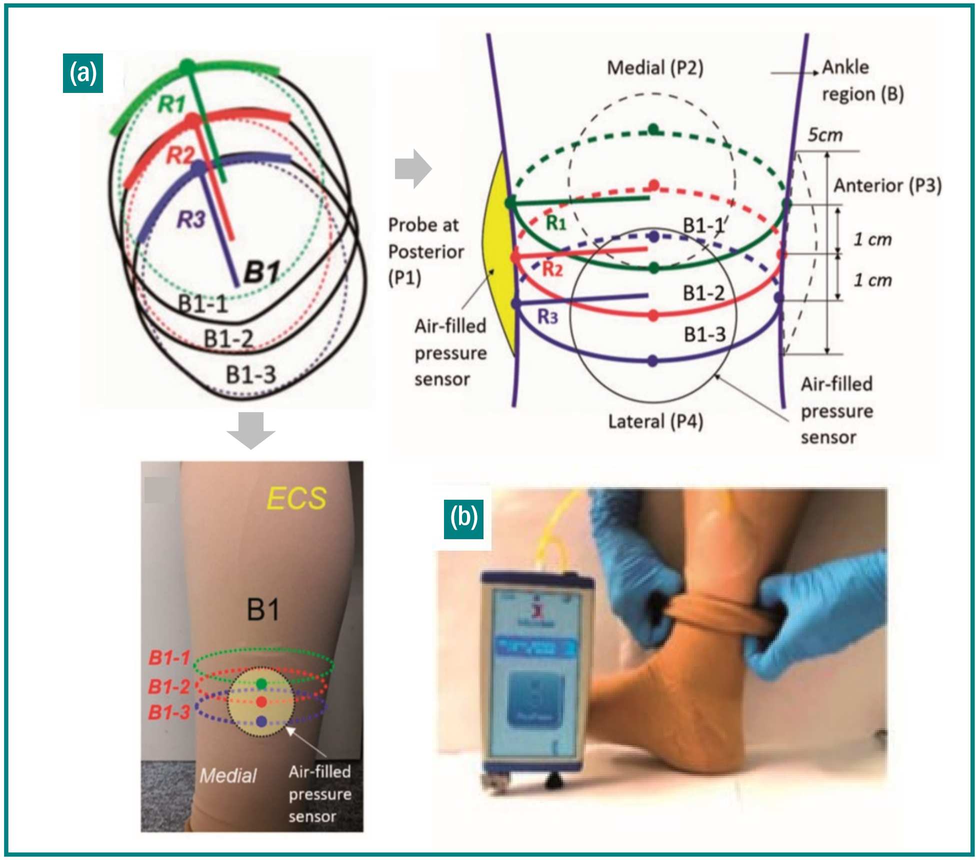
$$P_{skin}(\mathrm{mmHg}) = \frac{2\pi \times T(\mathrm{N}) \times n \times 75}{2\pi \times RoC_{0\,mean}(\mathrm{cm}) \times W(\mathrm{cm})} = \frac{T(\mathrm{N}) \times n \times 471}{tC_{0\,mean}(\mathrm{cm}) \times W(\mathrm{cm})}$$

(a) Instron (4411) tensile testing provide the required parameter values in the formula *Pskin* (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:

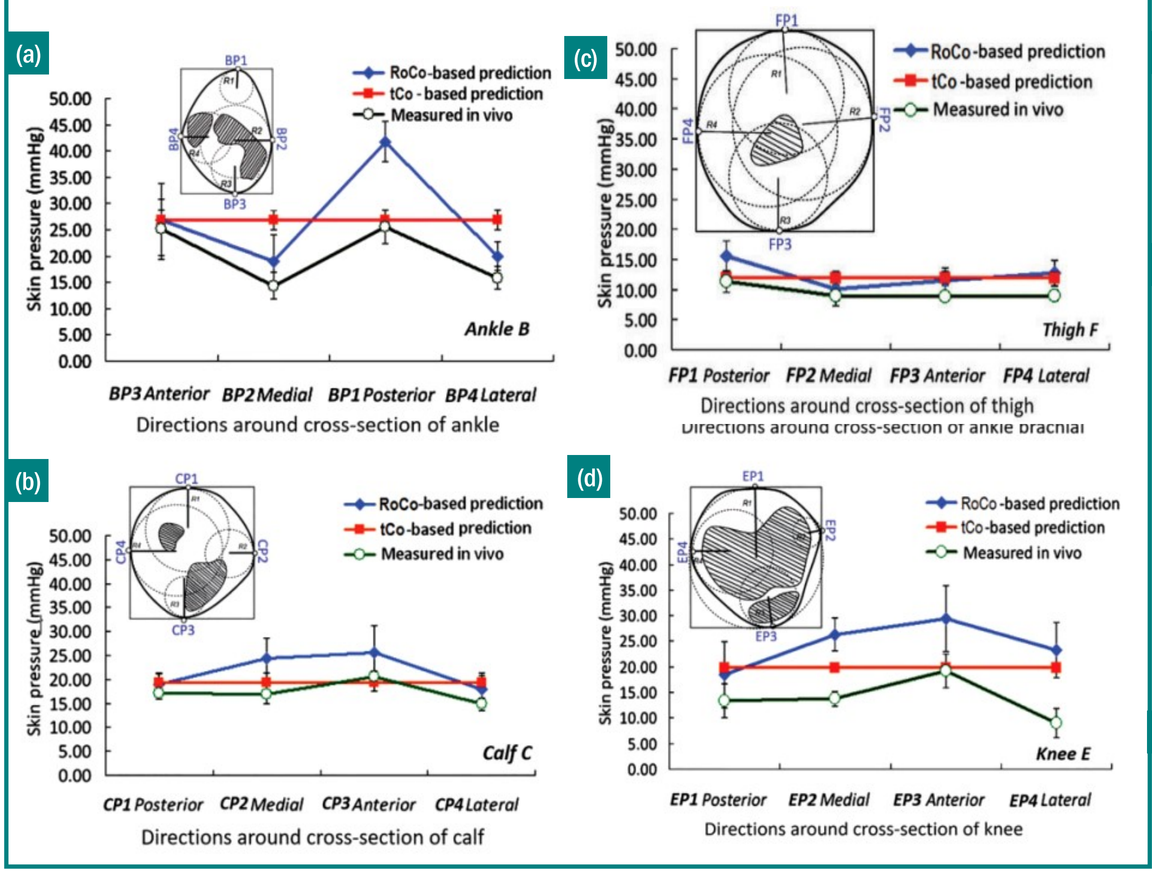
- Four directions: anterior, posterior, lateral, medial
- Five heights: ankle, brachial, calf, knee, thigh

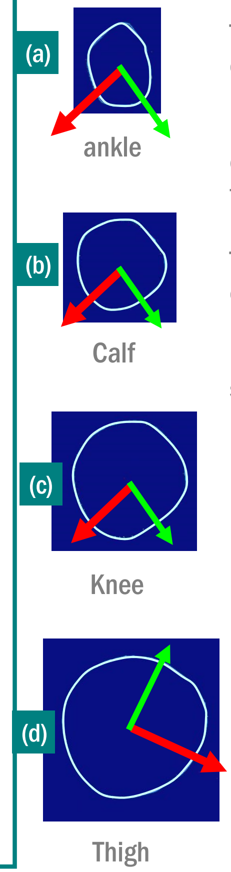
Research Methods and Materials

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

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

Comparison between predicted skin pressure with the measured pressure





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.

Digital cross-sectional images created by 3D leg scanning

Skin pressure prediction

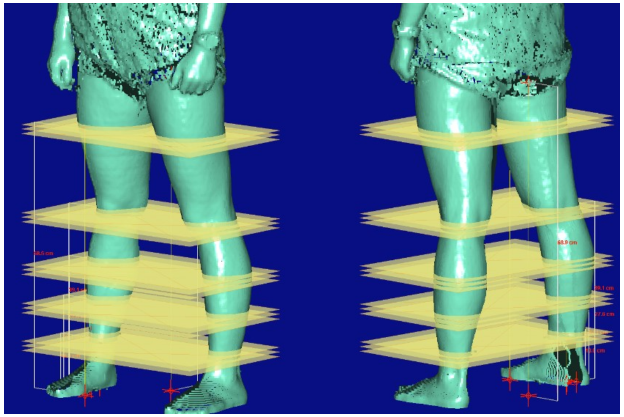
Research Methods and Materials

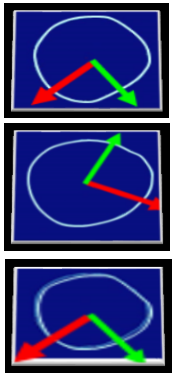
Stage I: Digital characterization of lower limb on geometry and morphology

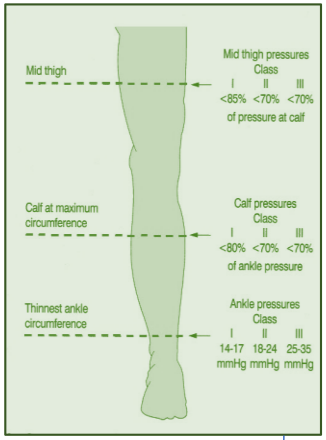
- Task 2: Strategy on stocking pressure prediction using leg surface curvature and geometry.

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

Pressure profile in different pressure classes (I, II, III) and longitudinal gradients







3D digital body scanning → Input → leg circumference & cross-sectional images → Output → Predicted skin pressures exerted by CS

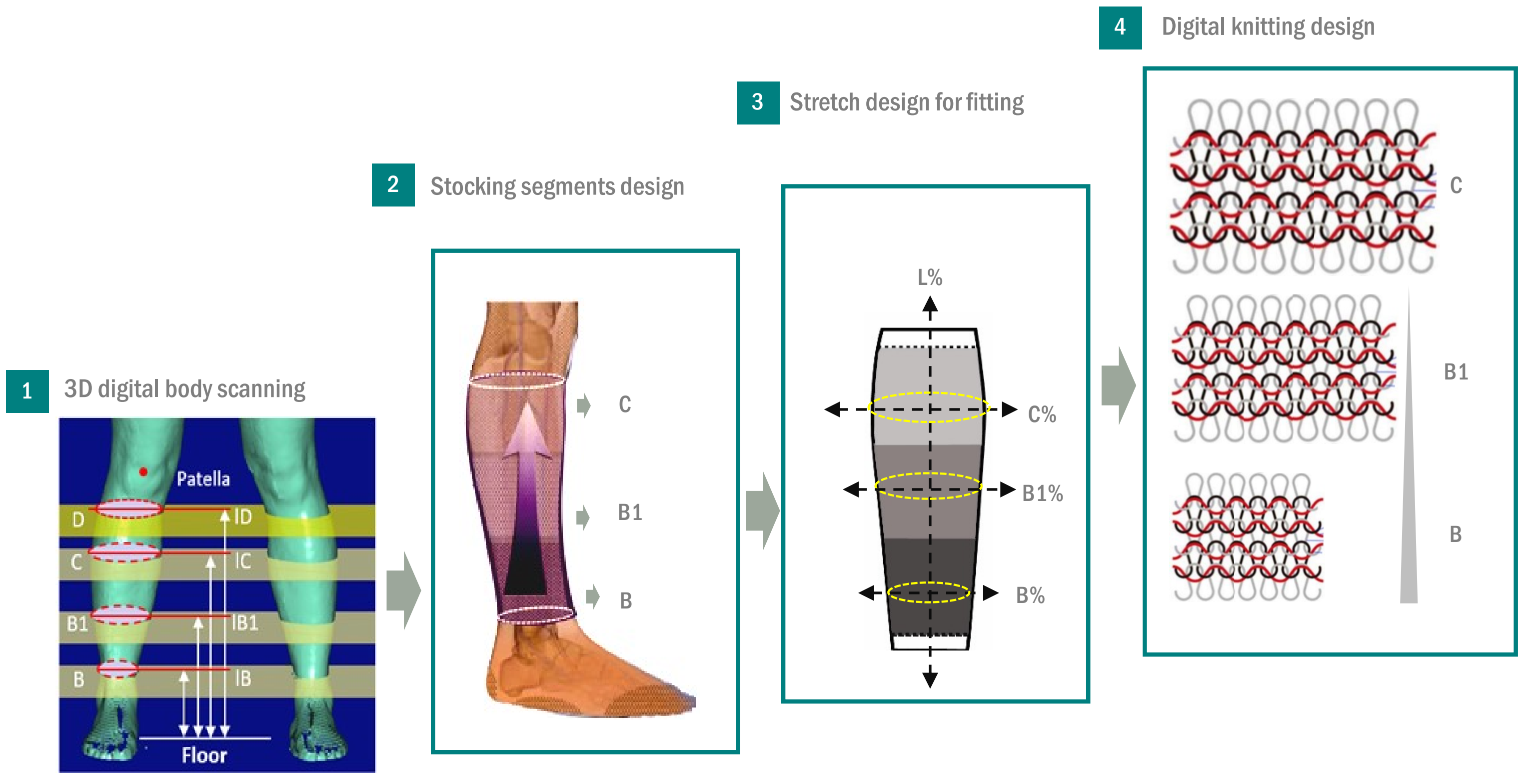
Input: Stocking material width & tension values

Output: Pre-assess stocking fit & pressure design before actual stocking production

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

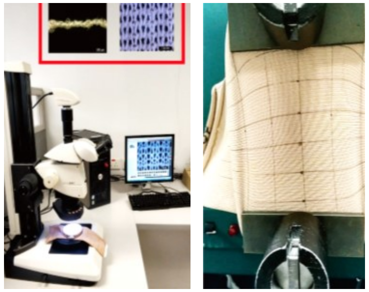


Research Methods and Materials

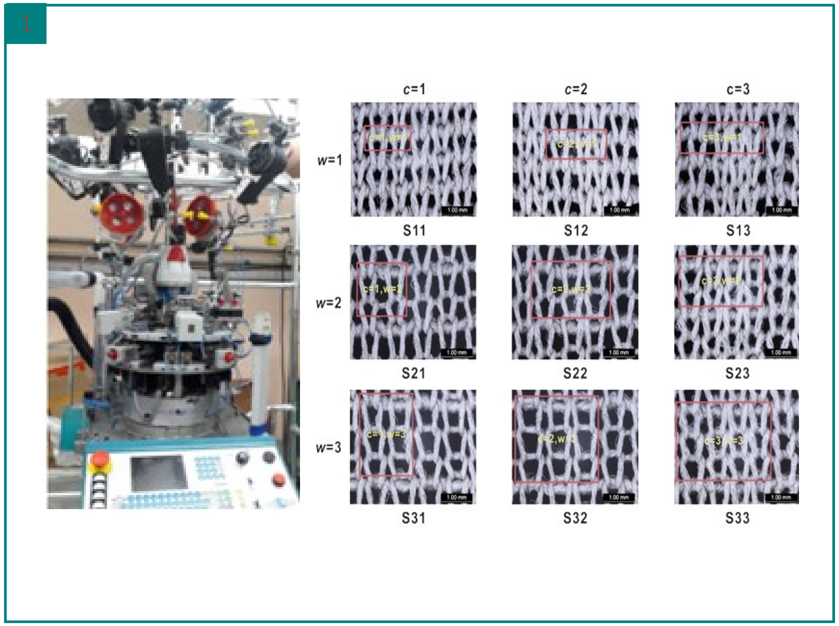
Stage II: Digitalized design and fabrication of custom-fitted compression stocking

- <u>Task 2</u>: Advanced 3D seamless digital knitting of custom-fitted stocking

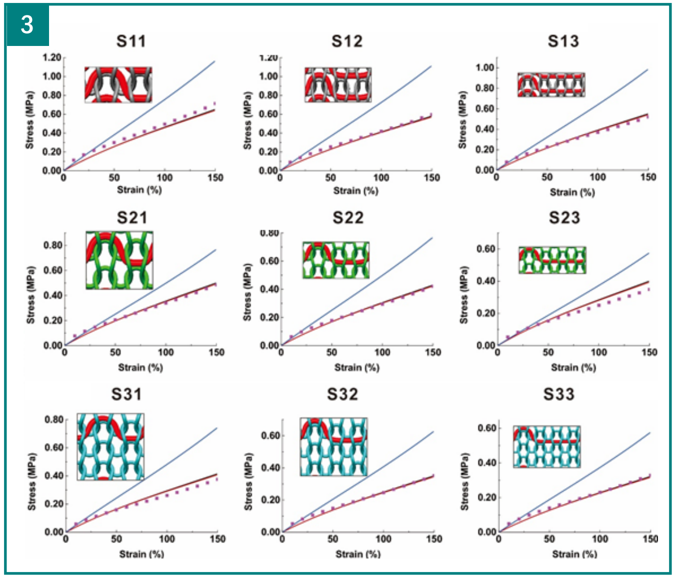
2



Microscopic structure analysis and tension test



Programmable circular knitting based on the parametric structural design.



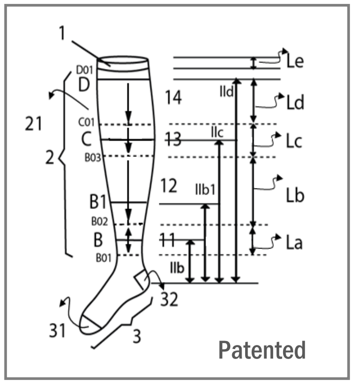
Mechanical (tension) properties of the designed laid-in fabrics.

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



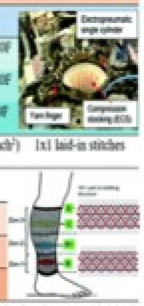
2

Classes	Linear density of ground elastomers (set at all 4 feeders)		Linear density of inlay elastomers (set at the 1st and 3rd feeders)	
	Core thread	Covered threads*	Core thread	Covered threads*
I	44 dtex	44 dtex/44 dtex/40F	233 dtex	44 dtex/ 44 dtex /40F
II	44 dtex	44 dtex/44 dtex/40F	294 dtex	44 dtex /44 dtex /40F
III	178 dtex	44 dtex/44 dtex/40F	405 dtex	22 dtex/22 dtex /20F

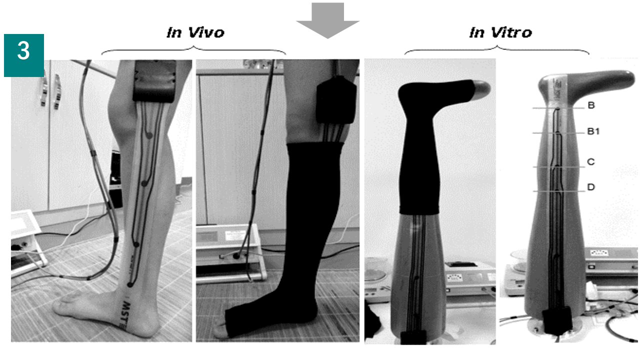
Gradient zones	Pressure residual ratio (%) **	Knitting height of zone (mm)	Mean knitting densities (stitches/inch²)		
			Class I	Class II	Class III
Zon-1	100	86	3858	3561	3032
Zon-2	100-70	84	3116	2612	2574
Zon-3	50-80	90	2632	2522	2152

1x1 laid-in stitches

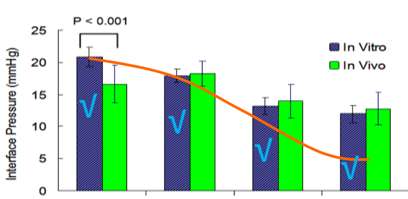
*Double covering: wrapping two spirals of non-elastic covered polyamide elastic threads in opposite directions around the elastic Lycra core. "dtex" indicates "decitex"; F indicates "filament"; **Standard GAL 3871.



3



4



Test points	B	B1	C	D
In vitro	20.86±1.57	17.91±1.11	13.21±1.31	12.00±1.37
RP (%)*	100 %	81.9 %	60.4 %	54.9 %
In vivo	16.33±2.86	18.21±1.96	13.96±2.66	12.73±2.51

* based on the mean value at each testing points

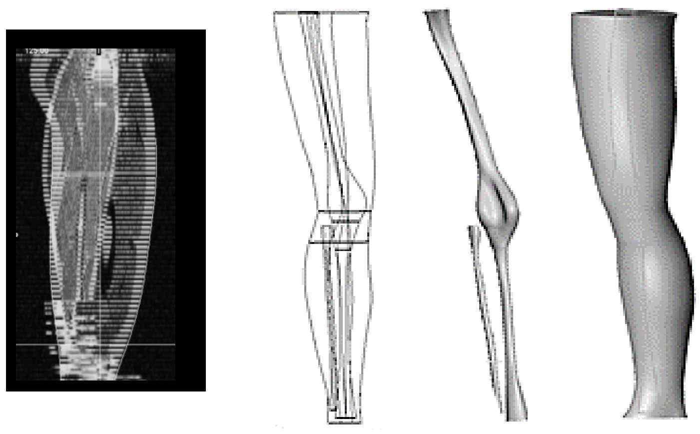
1. A patented pressure design and fabrication technology of CSs.
2. The designed knitting recipes for different pressure zones of CSs for pressure control.
3. CSs testing in vivo and in vitro.
4. Pressure gradient effect tested in vivo and in vitro.

Research Methods and Materials

Stage III: Finite element leg-compression stocking model

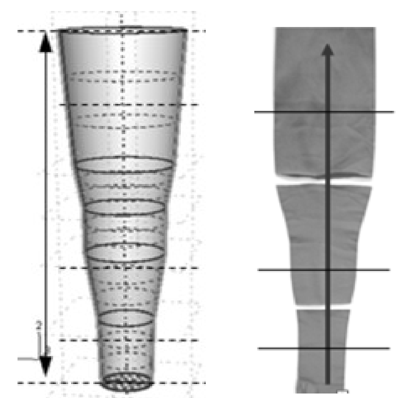
- Task 1: Leg-stocking geometrics reconstruction.

Extracted Magnetic Resonance Images of a real leg



3D biodigital leg model assigned with different biomaterial properties (bone and soft tissues).

Digitalized CS model with material properties



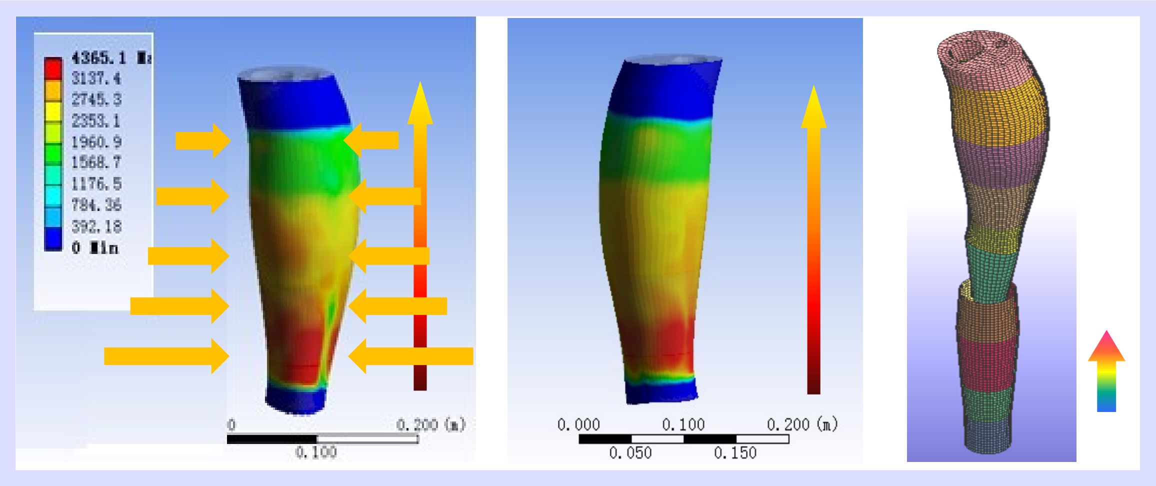
Segments	W(tonne/mm^3)	E_1 (N/mm^2)	E_2 (N/mm^2)	V	G_{12} N/mm^2)	T (mm)
Ankle	1.3×10^{-10}	0.2778	0.1969	0.2756	0.1741	1
Calf	1.1×10^{-10}	0.2138	0.1500	0.3261	0.1101	1
Knee	0.96×10^{-10}	0.1498	0.1031	0.3766	0.0461	1
Thigh	0.85×10^{-10}	0.1474	0.0957	0.3766	0.0400	1

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

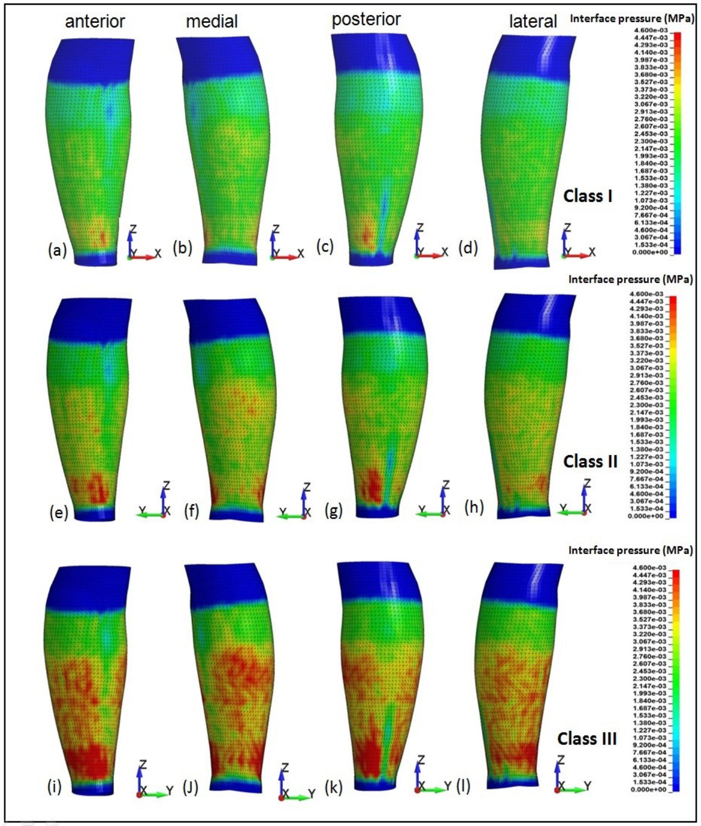
- Task 2: Biomechanical visualization of the designed CSs.

CSs material parameters input

Output

Pressure Classes	Gradient levels	W*($\times 10^{-10}$ tonne/mm^3)	E_1(MPa)	E_2(MPa)	G_{12} (MPa)	V	T (mm)
(I) Mild pressure	Ankle-B	3.25 ± 0.12^	0.28 ± 0.02	0.19 ± 0.02	0.11 ± 0.01	0.27 ± 0.02	
	Brachial-B1	2.75 ± 0.11	0.21 ± 0.02	0.15 ± 0.01	0.08 ± 0.01	0.33 ± 0.03	1.0 ± 0.1
	Calf-C	2.30 ± 0.10	0.15 ± 0.01	0.10 ± 0.01	0.05 ± 0.01	0.37 ± 0.03	
(II) Moderate pressure	Ankle-B	3.57 ± 0.13	0.35 ± 0.02	0.21 ± 0.02	0.14 ± 0.01	0.25 ± 0.02	
	Brachial-B1	3.02 ± 0.13	0.27 ± 0.03	0.15 ± 0.01	0.11 ± 0.01	0.27 ± 0.02	1.1 ± 0.2
	Calf-C	2.53 ± 0.11	0.19 ± 0.0	0.09 ± 0.01	0.07 ± 0.01	0.29 ± 0.01	
(III) Strong pressure	Ankle-B	3.74 ± 0.14	0.41 ± 0.03	0.17 ± 0.02	0.17 ± 0.01	0.23 ± 0.01	
	Brachial-B1	3.16 ± 0.13	0.32 ± 0.03	0.13 ± 0.01	0.13 ± 0.01	0.25 ± 0.02	1.2 ± 0.2
	Calf-C	2.65 ± 0.11	0.22 ± 0.02	0.08 ± 0.01	0.08 ± 0.01	0.27 ± 0.01	

Longitudinal biomechanical visualization of multi-class (I,II, III) CSs pressure

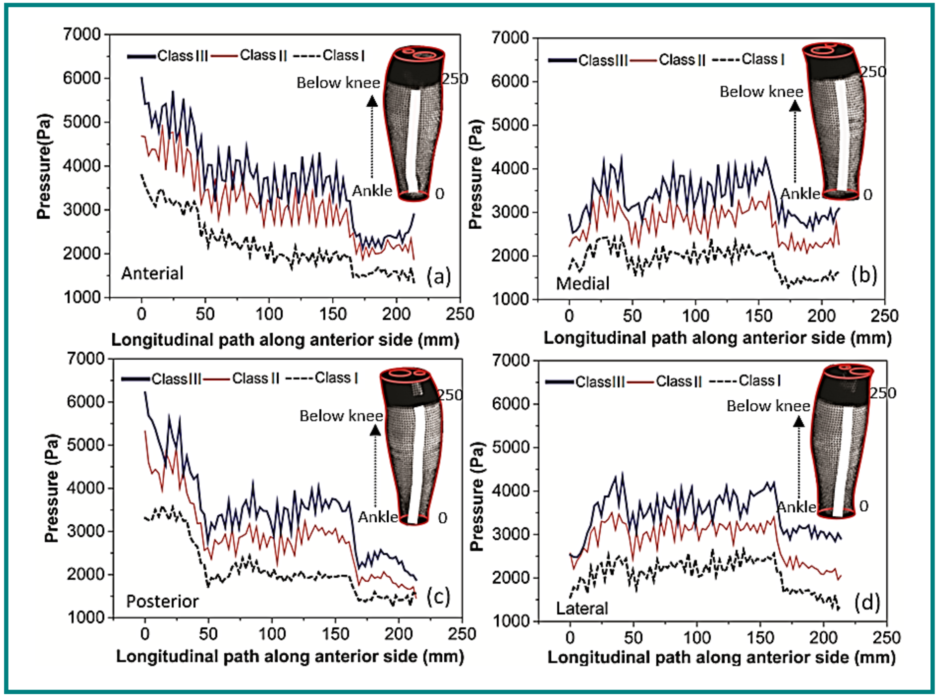


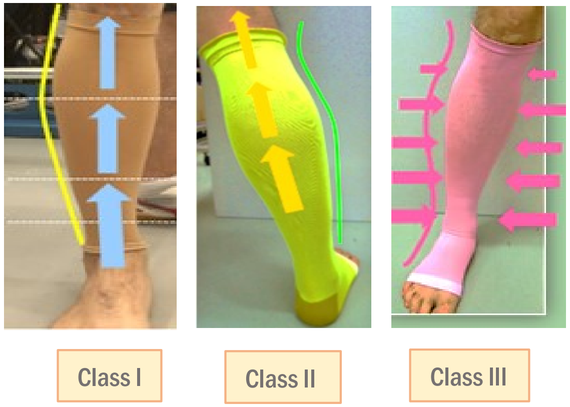
Research Methods and Materials

Stage III: Finite element leg-compression stocking model

- Task 2: Biomechanical visualization of the designed CSs.

Output → Digitalized skin pressure profiles at four directions around leg when being treated with 3 pressure classes (I, II, III) of CSs





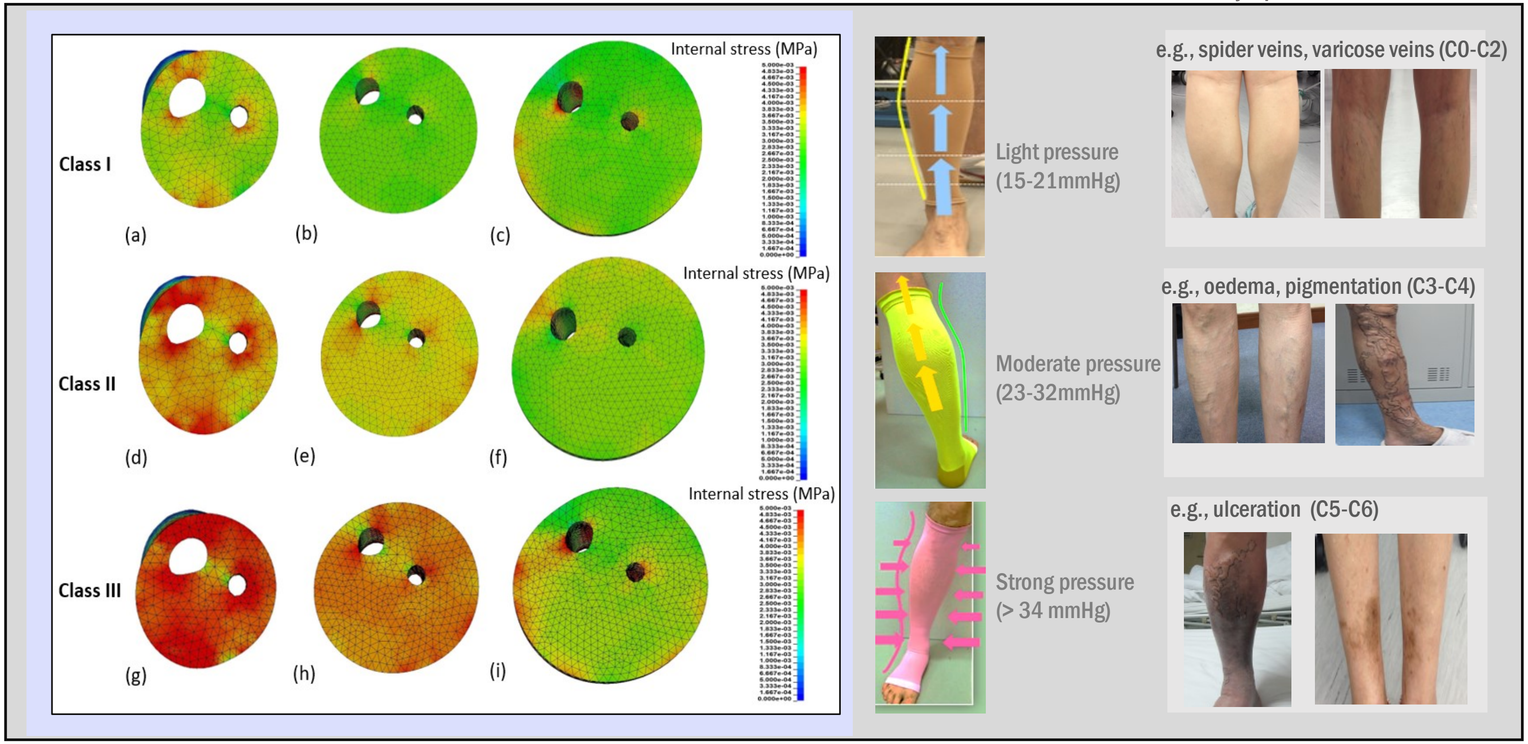
Research Methods and Materials

Stage III: Finite element leg-compression stocking model

- Task 2: Biomechanical visualization of the designed CSs.

Output → Biomechanical visualization: internal tissue stresses by the CSs with multi pressure classes (I, II, III)

CVI symptoms: CEAP C0-C6

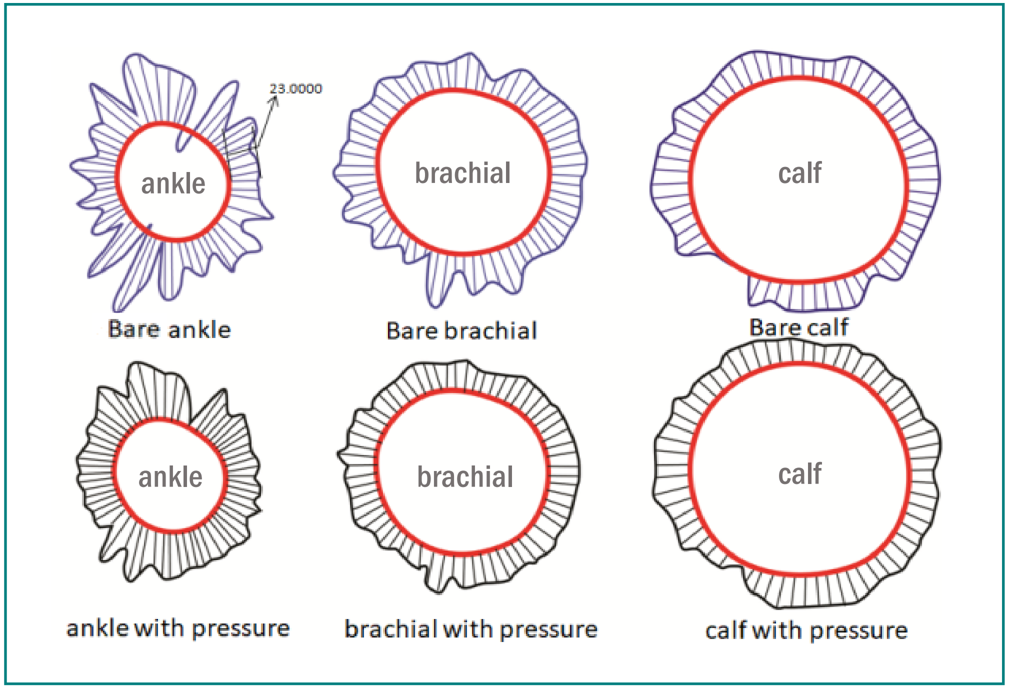


Research Methods and Materials

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



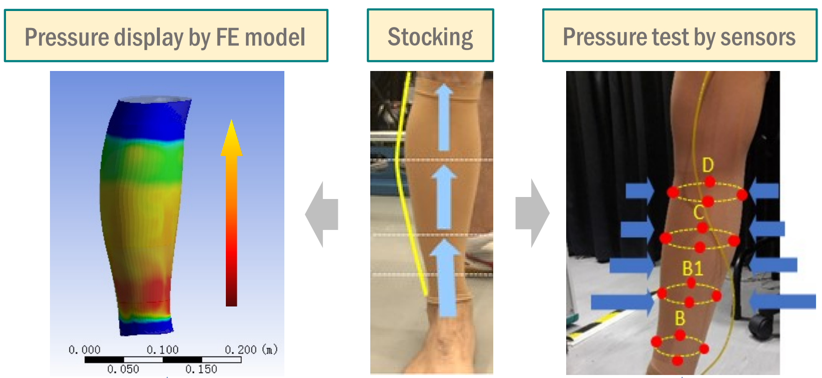
Skin surface curvatures

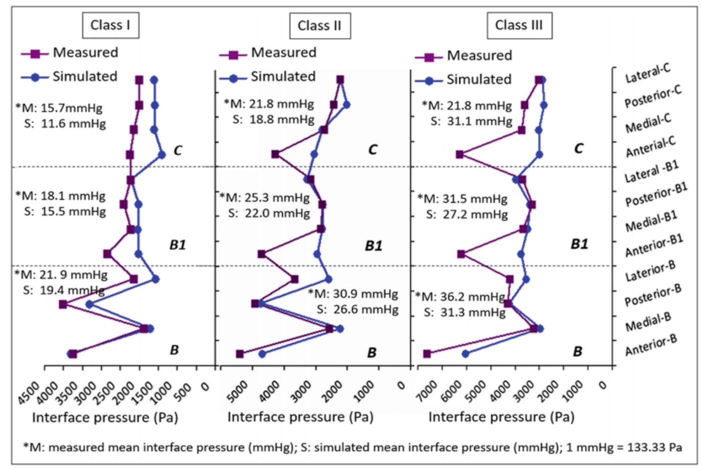
Research Methods and Materials

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





Digitalized leg model

Experimental measurement

Comparison

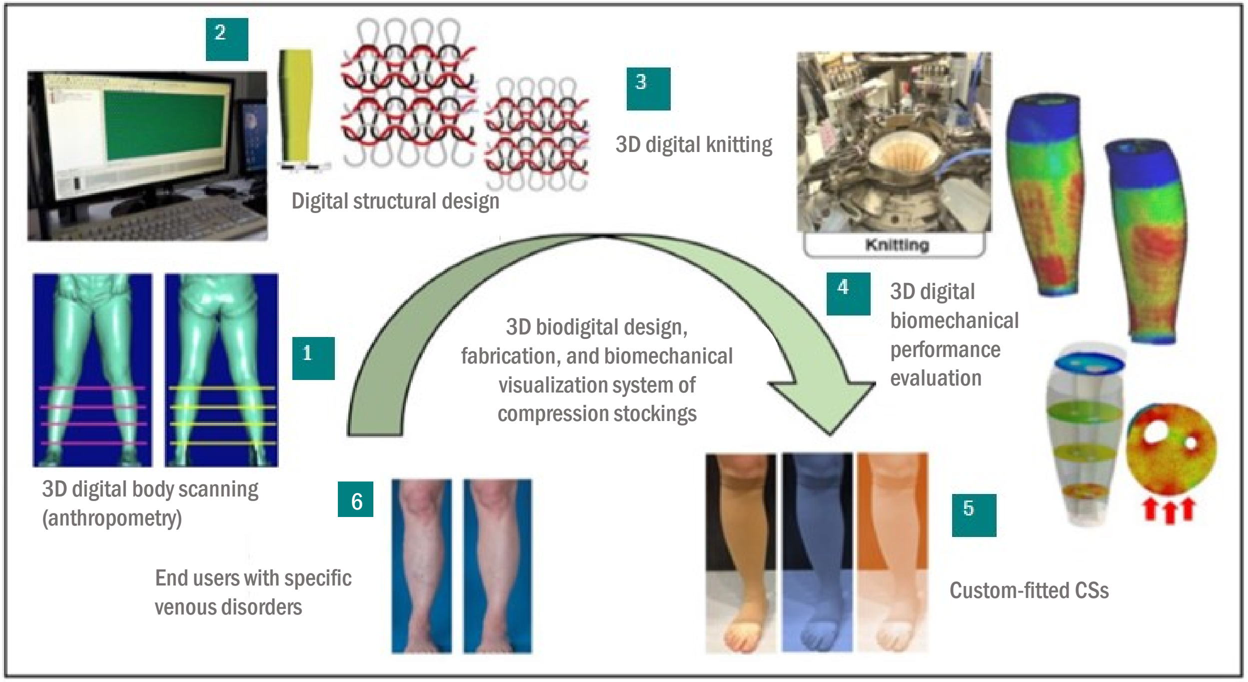
An agreement between the simulated and measured skin pressures

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

Research Methods and Materials

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.

東華三院 Tung Wah Group of Hospitals

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.

<u>Task 2:</u> User feedback analysis and follow-up.

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

東華三院 Tung Wah Group of Hospitals

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)

(1) 2019 **R LIU***, B XU, CY YE. Biodigital Design and Functional Visualization of Multi-Class Personalized Compression Textiles for Ergonomic fit. In: Di Bucchianico G. (eds) Advances in Design for Inclusion. AHFE 2019. Advances in Intelligent Systems and Computing, Vol 954, Cham. DOI_10.1007/978-3-030-20444-0_51. https://qrgo.page.link/AAWqG

(2) 2018 **R LIU***, B XU. 3D digital modeling and design of custom-fit functional compression garment. In: Wong W. (eds) Artificial Intelligence on Fashion and Textiles. AIFT 2018. Advances in Intelligent Systems and Computing, Vol 849. Springer, Cham. DOI: _ 10.1007/978-3-319-99695-0_20. https://qrgo.page.link/TisMe

(3) 2018 **R LIU***, JD LIU, TT LAO, M YING, XB WU. Determination of leg cross-sectional curvatures and application in pressure prediction for lower body compression garments. Textile Research Journal 2018, Vol 89 (10) 1835-1852.

(4) 2018 T WANG, FY LIANG*, **R LIU**, SS SIMAKOV, XC ZHANG, H LIU. Model-based study on the hemodynamic effects of graduated compression stockings in supine and standing positions. 2018 IEEE EMBS Conference on Biomedical Engineering and Sciences IECBES 2018, Malaysia, 3-6 Dec. 2018. https://qrgo.page.link/Lk7QZ

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)

(5) 2019 **R LIU***, SY LU, M YING. Novel adaptive, customized and proactive compression for treatment of venous disorders. Journal Basic & Clinical Pharmacology & Toxicology 2019, Vol 124 (S3). IERI International Conference on Medical Physics, Medical Engineering and Informatics (ICMMI), Tokyo, Japan. 22-24 Mar.2019.

(6) 2017 **R LIU***. Advanced compression textiles for physiotherapy and performance enhancement. Proceedings of Asia and Africa Science Platform Program Conference. Kyoto, Japan, 16-17th.Mar. 2017, pp 3-8.

(7) 2013 **R LIU***, TT LAO, SX WANG. Impact of weft laid-in structural knitting design on fabric tension behavior and interfacial pressure performance of circular knits. Journal of Engineered Fibers and Fabrics 2013;8(4):96-107.

(8) 2013 **R LIU***, TT LAO, SX WANG. Technical knitting and ergonomical design of 3D seamless compression hosiery and pressure performances in vivo and in vitro. Fibers and Polymers 2013;14(8): 1391-1399.

Dissemination and distribution of outcomes

Invited Speaker (3)

(1) 2018 Invited Speaker (**R LIU**) "3D Modeling of Custom-fit Functional Compression Garment". Artificial Intelligence on Fashion and Textile Conference 2018, 3-6 July 2018, Hong Kong. https://qrgo.page.link/427Vw

(2) 2018 Invited Speaker (**R LIU**), "Functional Compression Textiles: from Concept, Design to Product". Bright Sun Global Group Limited, Panyu, China, 25th.April 2018.

(3) 2017 Invited Speaker **(R LIU),** "Functional Legging for a Better Life". The 80th Anniversary large-scale Open Day of the Hong Kong Polytechnic University, 3rd. Dec. 2017. https://qrgo.page.link/xkaEq

Dissemination and distribution of outcomes

Patents (3)

(1) 2014 **R LIU**, A CHU. A type of compression hosiery, fabrication method, and seamless circular knitting machine, CN103564666B, State Intellectual Property Office of the P.R.C., 10th. June 2015.

(2) 2016 **R LIU**, X GUO, TT LAO, T LITTLE, D TANG, XY WANG. “A type of compression orthesis” (CN205884729 U), State Intellectual Property Office of the P.R.C., 2nd.Nov.2016.

(3) 2016 **R LIU**, X GUO, TT LAO, T LITTLE, D TANG, XY WANG. “A type of compression therapeutic device and fabrication method” (201611167916.1), State Intellectual Property Office of the P.R.C., 16th.Dec.2016.

Dissemination and distribution of outcomes

Awards (2)

Year	Events
2018	"Best Paper Award", (**R LIU***, B XU), "3D Modeling of Custom-fit Functional Compression Garment" by Artificial Intelligence on Fashion and Textile Conference, 3-6 July 2018, Hong Kong. https://qrgo.page.link/427Vw
2017	"Innovation & Product Development Award" (**R LIU**) by Hong Kong Textile Leading Industry for the developed "Modern Integrated Compression Orthesis", 5th.Dec. 2017, Hong Kong.

Dissemination and distribution of outcomes

Commercialization

Year	Events
2017-2019	Industrial companies (e.g., Health Pathways Group) commercialized the developed compression stockings.

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

General Research Fund/Early Career Scheme (GRF/ECS) (Principle Investigator) “Design Optimization of Comfort and Mechanical Function of Compression Stockings for Seniors” (2019-2021), support 1 PhD student and 2 Research Staffs in 3-year project work.

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

1. Sabina O, Elena S, Emilia F, et al. Virtual fitting- innovation technology for customize clothing design. Procedia Engineering 2014; 69: 555-564.
2. Fontana M, Rizzi C, Cugini U. 3D virtual apparel design for industrial applications. Computer-Aided Design 2005; 37:609-622.
3. Liu YJ, Zhang DL, Yuen MMF. A survey on CAD methods on 3D garment design. Computers in Industry 2010; 61:576-593.
4. R Liu, B XU. 3D digital modeling and design of custom-fit functional compression garment. In: Wong W. (eds) Artificial Intelligence on Fashion and Textiles. AITA 2018. Advances in Intelligent Systems and Computing, Vol 849. Springer, Cham. Computation in Bioengineering. https://qrgo.page.link/TisMe.
5. Winslow R, Trayanova N, German D, et al. Computational medicine: translating models to clinical care. Sci Transl Med 2012; 4(158): 158rv11.
6. Grinberg L, Cheever E, Anor T, et al. Modeling blood flow circulation in intracranial arterial networks: A Comparative 3D/1D simulation study. Annals of Biomedical Engineering 2010: DOI: 10.1007/s10439-010-0132-1.
7. Mauck J, Wieding J, Kluess D, et al. Numerical simulation of mechanically stimulated bone remodeling. Current Directions in Biomedical Engineering 2016; 2(1): DOI: 10.1515/cdbme-2016-0141.
8. Flynn C, Stavness I, Lloyd J, Fels S. A finite element model of the face including an orthotropic skin model under in vivo tension. Computer Methods in Biomechanics and Biomedical Engineering 2013; 45(6): DOI: 10.1080/10255842.2013.820720.
9. Zion Market Research. Global compression garments and stockings market set for rapid growth, to research around USD 3,216.7 million by 2022. Accessed on 2nd.Jan.2018 via link https://www.zionmarketresearch.com/news/compression-garments-stockings-market.
10. Caggiati A, Rosi C, Heyn R, Franceschini M, Acconcia MC. Age-related variations of varicose veins anatomy. J Vasc Surg 2006: 44(6):1291-1295.

References

11. Perlowski AA, Jaff MR. Vascular disorders in athletes. Vasc Med 2010: 15(6):469-479.
12. Smyth R, Aflaifel N, Bamigboye A. Interventions for varicose veins and leg oedema in pregnancy. Cochrane Database Syst Rev 2015, 10.1002/14651858.CD001066.pub3.
13. Amsler F, Blättler W. Compression therapy for occupational leg symptoms and chronic venous disorders-a meta-analysis of randomized controlled trials. Eur J Vasc Endovasc Surg 2008; 35: 336-372.
14. Liu R, Kwok YL, Li Y, Lao TT, Zhang X, Dai XQ. Objective evaluation of skin pressure distribution of graduated elastic compression stockings. Dermatol Surg 2005; 31(6): 615-624.
15. Partsch H. Compression therapy: clinical and experimental evidence. Ann Vasc Dis 2012;5(4):416-422.
16. Raju S, Hollis K, Neglen P. Use of compression stockings in chronic venous disease: patient compliance and efficacy. Ann Vasc Surg 2007;21(6):790-795.
17. Mosti G, Partsch H. Duplex scanning to evaluate the effect of compression on venous reflux. Int Angiol 2010; 29:416-420.
18. Franks PJ, Oldroyd MI, Dickson D, Sharp EJ, Moffatt CJ. Risk factors for leg ulcer recurrence: a randomized trial of two types of compression stocking. Age Ageing 1995;24:490-494.
19. Tandler SF. Challenges faced by healthcare professionals in the provision of compression hosiery to enhance compliance in the prevention of venous leg ulceration. EWMA Journal 2016; 16(1): 29-33.