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Modern Compression Orthosis for Improving Comfort, Haemodynamic Efficacy & Preventing Knee Pain of Lower limbs

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PolyU UoA 38

Modern Compression Orthosis for Improving Comfort, Haemodynamic Efficacy & Preventing Knee Pain of Lower limbs

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Title: Modern Compression Orthosis for Improving Comfort, Haemodynamic Efficacy & Preventing Knee Pain of Lower limbs

Descriptor

Nearly 250 million people have osteoarthritis-related knee pain (KP), and 20%–40% of adults experience chronic venous insufficiency (CVI) worldwide. As part of our research project—the first of its kind in Hong Kong—clinical studies were conducted, and they revealed that over 60% of people aged 45 and above experience both KP and CVI simultaneously. However, to date, not a single solution has been proposed to address this combination of symptoms.

This research aimed to design and develop a modern compression orthosis called the “Leg Guarder Kit” by strategically integrating compression stockings and knee braces to improve blood circulation and relieve KP in the lower limbs. The study objectives were as follows: (1) to establish a novel stratified body-shape-driven sizing system [S4] adapted to the typical Asian morphology; (2) to create a new “Incudoknit” weaving structure that can control elastic moduli of the compression materials; and (3) to optimize the biomechanical design of the developed orthosis by applying advanced 3D hybrid weft-knitting technology for achieving effective pressure control, joint support, and ergonomic fit. The developed kit generated unique biaxial tension and double progressive compression to the lower limbs, thereby stabilizing the skeletal muscles, increasing mobility, and promoting venous hemodynamics in practice.

The newly developed orthosis has already benefited over 300 people with CVI and KP (elderly people, athletes, nurses, care workers, teachers, office clerks, and electricians). The research outcomes have been recognized by the clinical communities and design industry, including the Tung Wah Group of Hospitals, Chemtax Industrial Co. Ltd., China Southern Power Grid, Hong Kong Innovation and Technology Commission, and an award committee of the International Exhibition of Inventions of Geneva (Switzerland). This project has attracted HK$ 4.5M in funding from the relevant industries and the Hong Kong SAR Government. The outputs have yielded ten publications, four patents, one design award, and one industrial standard. Our invention underpinned a new business of the Health Pathways Group and was first launched in 2018.

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 research work presents a newly designed and developed modern compression orthesis (i.e., integrative compression stocking and knee brace) for prevention and relief of the mixed chronic venous insufficiency (CVI) and knee pain (KP) symptoms, to improve user comfort, motion, self-care, and leg health in daily life.

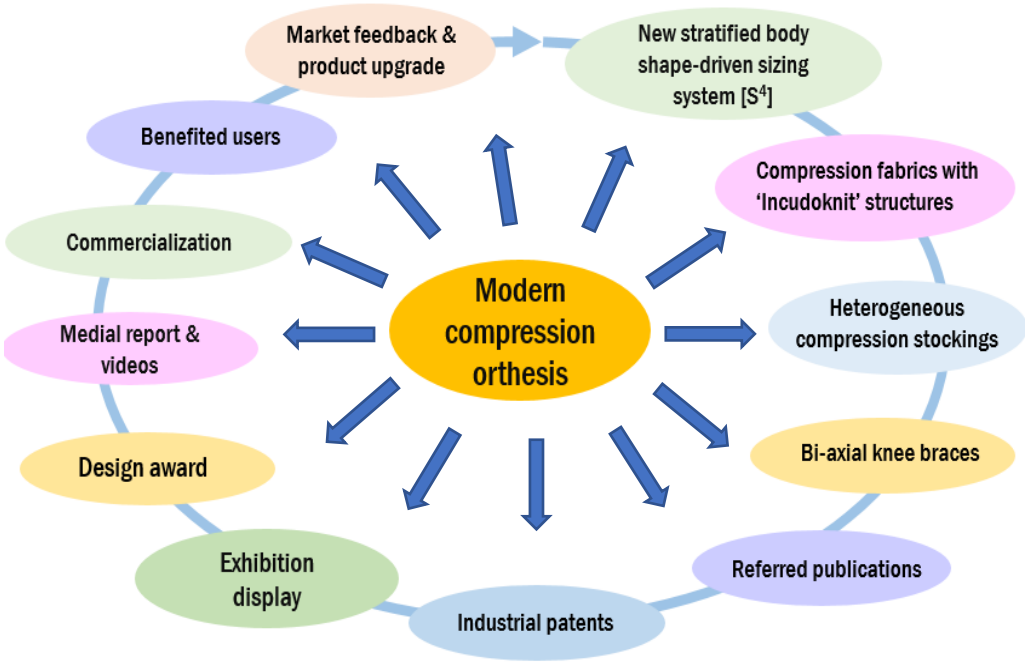
Research Questions

The research sets out to explore:

- How compression textile modalities can be effectively designed to prevent and relieve concurrent symptoms of CVI-KP?
- How to design ergonomic comfort of compression textile products to fit users with diverse body shapes?
- How to control pressure dosages and supportive forces to lower limbs through customized structural and material design?
- How to optimize the functional performances of compression textiles to improve user compliance, blood circulation (hemodynamics), and relieve knee pain feeling?

Research Output / Body of Work

- 600+ sets of the developed modern compression orthoses for people with CVI-KP symptoms.
- 10 publications in multidisciplinary fields of textiles, healthcare, clinical medicine, ergonomics, and human factors.
- 4 patents on fabrication methodologies of compression stocking, knee brace, and integrative compression orthesis.
- 3 International exhibitions displaying the designed compression orthesis “Leg Guarder Kit”.
- 1 design award in an international invention exhibition.
- 7 media reports on compression orthesis.
- 2 videos on research output.
- 4 invited public talk.
- 1 new industrial consultancy project based on the output.
- 1 national industry standard.
- 1 new business (company) underpinned by the output.
- 300+ benefited Asian users.



Research Output / Body of Work

Design Innovation

- Established new stratified body-shape driven sizing system ([S^4]) especially for Asian users.
- Created “Incudoknit” weaving structures for realizing hybrid material stiffness for different pressures and forces delivered to the targeted body zones.
- Optimized biomechanical design for reshaping pressure distribution and joint support to enhance venous hemodynamics and knee support of the lower limbs.
- Applied 3D circular seamless and flat-bed knitting technologies for the effective mechanical control of compression orthesis.
- Determined medical-grade elastomers and skin-friendly materials for enhanced ergonomic-fit and wearing comfort.
- Developed compression orthesis with integrative compression stocking with “double progressive pressure” and knee brace with “bi-axial” tension control.

Research Fields and Key Works Referenced

This research fields include:

(1) Epidemiological and pathophysiological survey on CVI-KP symptoms.

(2) Biomechanical study on the vascular and musculoskeletal system of lower limb.

(3) Mechanisms analysis of compression and physical intervention therapy.

(4) Asian body shape survey, analysis, and clothing sizing system.

(5) Biomedical textile design for healthcare, medical and rehabilitation.

(6) Elastic polyamide materials screening, assessment, and design.

(7) 3D hybrid seamless circular-flat bed knitting and structural design.

(8) Physical-mechanical property test of compression textiles.

(9) Psycho-physiological and clinical trials and assessment.

(10) User feedback analysis and design optimization.

Research Fields and Key Works Referenced

Chronic Venous Insufficiency (CVI)

CVI is a most common chronic disease, affecting 20%-40% in adults[1-2]. CVI refers to the malfunction of venous valves in the veins, causing various symptoms such as swelling, pain, tiredness, discomfort, and varicose veins in the lower limbs. Sitting or standing for extended periods results in increased venous hypertension, venous stasis, and reduced venous return to the heart.

Osteoarthritis related Knee Pain (KP)

KP affects approximately 25% of adults[4] and is a leading cause of disability in people over 50 years[5]. Knee osteoarthritis is the most common cause of the KP and functional impairment[6]. Studies have demonstrated that older patients with severe knee osteoarthritis have significantly more severe KP and lower health-related quality of life[7].

Mixed CVI-KP Symptoms

Clinical studies in our research project—the first of its kind in Hong Kong—have indicated that over 60% of people 45 years and older experience both KP and CVI. This finding is consistent with that of Al-Omari[8], who reported that knee osteoarthritis is significantly associated with CVI. Lower limb overuse and prolonged inactivity (sitting or standing) exert pressure on the lower limb veins and increase the loading on the knee joints. These factors—in addition to age, obesity, and sex—increase the likelihood of the concurrence of CVI and KP[9,10]. However, so far, solutions to this concurrence are absent.

Research Fields and Key Works Referenced

Compression Intervention Therapy

Compression therapy has become the cornerstone for prophylaxis and treatment of CVI with aims to reduce edema and to improve venous and lymphatic return form the lower limbs [12,13]. The severity of CVI is classified by CEAP criteria (Clinical, Etiology, Anatomy, and Pathophysiology) into six clinical categories. That is, C0: no visible or palpable signs of venous disease; C1: reticular and spider veins; C2: varicose veins; C3: edema/swelling; C4: evidence of venous stasis skin changes; C5: healed venous stasis ulceration; C6: active venous ulceration[14]. Different intervention modalities, such as CSs, compression bandages, and pneumatic pumps, have been applied as compression therapy for CVI of varying severities. Among these modalities, compression stockings (CSs) with various pressure classes (15–40 mmHg) are most commonly applied to all stages of CVI because of their low profile, cost-effectiveness, and ability to continually deliver mobile pressure [15].

In the treatment of osteoarthritis-related KP, nonsurgical biomechanical approaches that achieve sustained reduction of medial knee loading are recommended[16]. Knee bracing is a user-friendly and commonly used physiotherapeutic modality for the relief of KP. Knee bracing changes the distribution of forces at the knee joint and is aimed at decreasing KP, slowing disease progression, and improving physical function, muscle cocontraction, proprioception, and body stability[17]. Commonly applied knee braces are of four major types: supportive, prophylactic, functional, and postoperative and rehabilitation knee brace. Studies have demonstrated the benefits of knee bracing intervention to KP and motion, but the balanced wearing comfort and mechanical effects of knee braces require further investigation.

Research Fields and Key Works Referenced

Research Gap

We conducted clinical screening, a market survey, and an extensive literature review, which revealed a research gap in the treatment of mixed CVI-KP symptoms. Furthermore, existing mechanical modalities for CVI-KP are associated with inadequate fit and low user compliance. These limitations are detailed as follows.

- High-non compliance for existing compression textile products due to poor fitting and discomfort, which reduces treatment effectiveness.
  e.g., only 21% of patients reported using CSs on a daily basis; 63% did not use at all or discontinued their use after the trial period [18].

- Poor fit not only reduces user compliance, but also produces side effects in use of compression products.
  e.g., too tight or peak pressure resulted in ischemia, and even ulceration at tibia region[19].

- Varying pressure dosage produced by compression products due to irregular lower limb shapes.
  e.g., CSs exerted insufficient or excessive pressure and resulted in the tourniquet effect, leading to skin damage and a reversed gradient in venous blood flow[20].

- Rigid materials and big volume limited leg motion in dynamic activities.
  e.g., rigid materials reduced frequency of use due to difficulties to take on-off, especially for the elderly with weak grip strength.

- No compression orthoses have been specially designed for Asian users.

Research Fields and Key Works Referenced

Dr. Rong Liu's contribution to the research are:

- Design and development of original compression orthesis (compression stocking and knee brace) for the targeted users.
- Biomechanical design and knitting structural design of compression textiles.
- Data collection, analysis, and report in the quality journals and conferences.
- Wear trials among users from Tung Wah Groups of Hospitals, China Southern Power Grid, Weihai Municipal Hospital, and the public society.
- Patent preparation, user feedback analysis, follow up, and product upgrading.
- Underpinned a new business, industrial standard, and product commercialization.

Research Team:

This research work requires multidisciplinary knowledge, skills, and approaches. The team member consist of medical doctor, rehabilitation expert, and materials and healthcare informatics professionals.

- Dr. Xia Guo (MB, DrMed, Germany), Department of Rehabilitation Sciences, the Hong Kong Polytechnic University, expertise in musculoskeletal tissue engineering, mechanobiology in bone regeneration, skeletal development, and rehabilitation device design.
- Prof. Terence T Lao (MBBS, MD, MRCOG, FRCOG, Cert.in Maternal-Fetal Medicine (Toronto)), the Chinese University of Hong Kong, expertise in the obstetrics and gynecology, compression therapy, and wearing comfort assessment.
- Prof. Trevor Little (PhD), Wilson College of Textiles, North Carolina State University, expertise in performance materials, fashion and textiles design, technology, and product development.
- Dr. Michael Ying (PhD), Department of Health Technology and Informatics, the Hong Kong Polytechnic University, expertise in ultrasound imaging diagnosis and monitoring of the disordered organs.

Research Methods and Materials

Stage I: Target user investigation.

- Task 1: Clinical screening of CVI-KP symptoms of the targeted users.
- Task 2: Buildup of the stratified body shape-driven sizing system [S4] for Asian.

Stage II: Design and development of compression orthesis.

- Task 1: Biomechanical design of modern compression orthesis.
- Task 2: Digital knitting structure design and material testing for suitable quality fabrics.
- Task 3: Hybrid weft-knitting fabrication of different orthesis prototypes.

Stage III: Performance assessment of compression orthesis on users.

- Task 1: Lab assessment of hemodynamics and muscular activities using new compression stocking & knee brace.
- Task 2: Comfort and clinical surveys on the developed compression orthesis.

Stage-IV: User feedback analysis and design optimization.

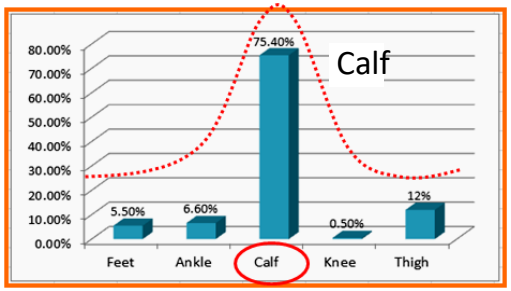
Research Methods and Materials

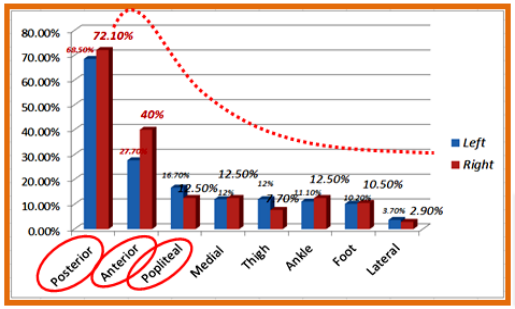
Stage I: Target user investigation.

Task 1: Clinical screening of CVI-KP symptoms of the targeted users.

A large-scale CVI-KP symptoms screening among the target users for building design evidence of compression orthesis.

Posterior & Anterior calf: High prevalence of CVI





Self-health report and survey

Subjects with both CVI & OA knee	60%
Female	74%
Male	26%

OA Knee	60 %
Female	70 %
Male	44 %

Symptoms (CEAP)	Proportion
C1	38 %
C2	60 %
C3	2 %

Knee joint & vein system assessment

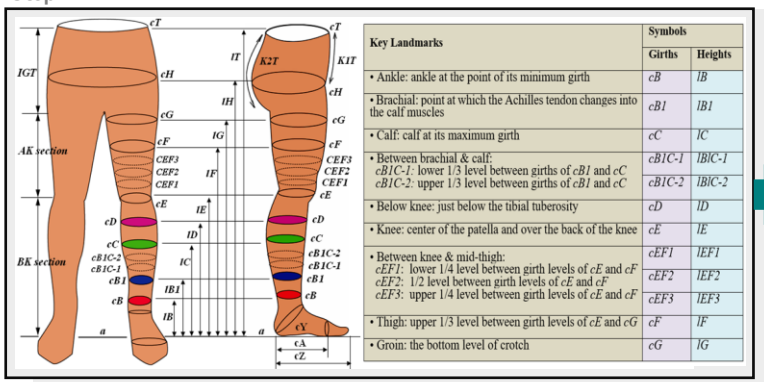
Research Methods and Materials

Stage I: Target user investigation.

Task 2: Buildup of a stratified body shape-driven sizing system [S4] for Asian body

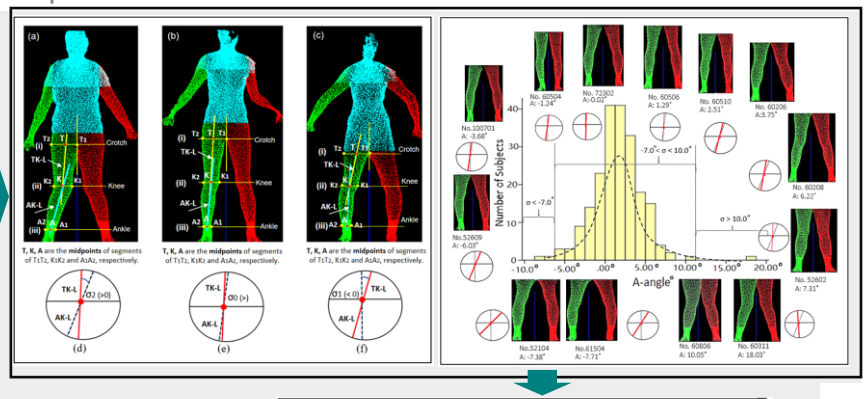
Step 1. Key landmarks determination, Step 2. 3D digital body scanning
Step 3. Multiple interpolation simulation algorithms, Step 4. Lower limb shape and size classification

Step 1

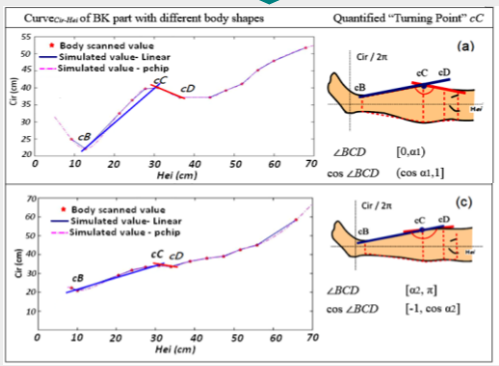


Key Landmarks	Symbols	
	Girths	Heights
• Ankle: ankle at the point of its minimum girth	*cB*	*lB*
• Brachial: point at which the Achilles tendon changes into the calf muscles	*cB1*	*lB1*
• Calf: calf at its maximum girth	*cC*	*lC*
• Between brachial & calf: *cB1C-1*: lower 1/3 level between girths of *cB1* and *cC* *cB1C-2*: upper 1/3 level between girths of *cB1* and *cC*	*cB1C-1* *cB1C-2*	*lB1C-1* *lB1C-2*
• Below knee: just below the tibial tuberosity	*cD*	*lD*
• Knee: center of the patella and over the back of the knee	*cE*	*lE*
• Between knee & mid-thigh: *cEF1*: lower 1/4 level between girth levels of *cE* and *cF* *cEF2*: 1/2 level between girth levels of *cE* and *cF* *cEF3*: upper 1/4 level between girth levels of *cE* and *cF*	*cEF1* *cEF2* *cEF3*	*lEF1* *lEF2* *lEF3*
• Thigh: upper 1/3 level between girth levels of *cE* and *cG*	*cF*	*lF*
• Groin: the bottom level of crotch	*cG*	*lG*

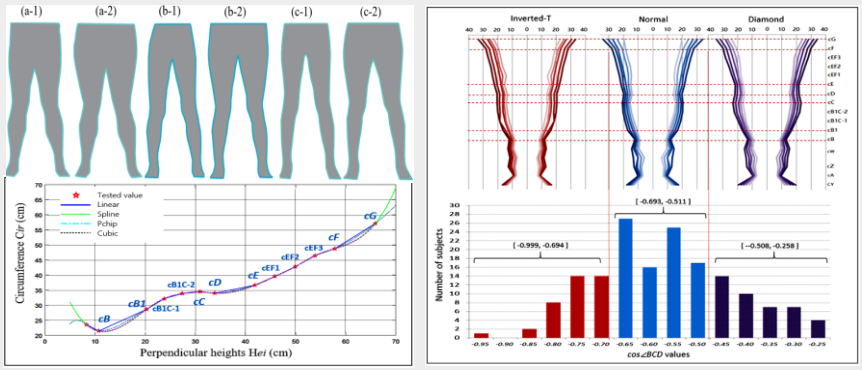
Step 2



Step 3



Step 4

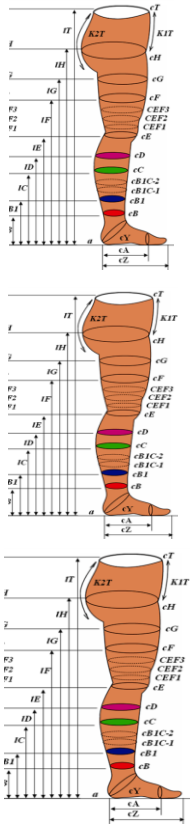


Research Methods and Materials

Stage I: Target user investigation.

<u>Task 2:</u> Buildup of a stratified body shape-driven sizing system [S4] for Asian.

Established a new sizing system of lower limbs for Asian



Cir (cm) with increased sizes (min., percentiles, Trimean, max.)

	Min.		25%		Trimean		75%		90%		97.5%		Max.		
Positions	I		II		III		IV		V		VI		VII		*Hei* (cm)
(1) Diamond															
cB	18.5		19.1		20.3		21.5		22.5		22.7		22.7		10.6
cB1	23.1		27.5		29.2		31.0		32.1		32.9		32.9		19.5
cC	31.9		33.5		36.0		37.2		40.2		40.3		40.3		29.0
cD	29.6		31.6		33.9		36.1		37.3		37.4		37.4		34.6
cE	32.2[a]	32.8[b]	34.9	34.9	37.2	37.4	39.1	40.4	40.4	41.9	40.9	42.8	41.2	43.1	41.9
cF	41.7	45.2	38.9	45.9	48.9	52.0	54.3	56.1	56.8	58.3	58.1	59.4	58.5	59.8	57.6
cG	48.0	52.0	52.0	56.1	54.7	58.8	56.9	64.3	58.7	66.8	59.6	68.0	59.9	68.4	64.6
(2) Balanced															
cB	16.7		18.9		19.9		20.8		21.6		23.6		24.1		10.5
cB1	21.7		24.8		26.2		27.5		28.9		31.6		33.4		19.8
cC	28.2		31.0		32.7		34.0		35.5		39.2		39.4		30.6
cD	27.3		30.7		32.3		33.7		35.4		39.2		39.4		34.8
cE	29.9[a]	32.3[b]	33.2	34.9	35.9	37.0	39.8	40.2	41.8	41.8	42.8	42.6	43.1	42.9	42.0
cF	37.3	43.4	41.4	46.5	46.2	49.9	49.7	52.6	52.1	54.4	53.4	55.4	53.8	55.7	58.5
cG	39.7	51.2	48.6	55.4	52.6	57.9	63.7	66.5	66.2	71.9	67.4	74.5	67.9	75.4	66.7
(3) Inverted trapezoid															
cB	18.0		19.3		20.2		21.4		22.5		24.4		24.8		10.4
cB1	23.7		26.1		27.4		28.9		32.5		34.9		39.8		19.5
cC	29.0		33.0		34.7		36.5		37.8		39.9		40.8		29.8
cD	27.4		31.7		33.3		35.5		36.3		38.0		39.3		34.2
cE	30.7[a]	33.1[b]	34.1	35.4	35.2	35.9	39.9	41.0	41.3	43.1	42.0	44.1	42.2	44.5	41.8
cF	38.7	42.9	43.0	45.9	45.8	47.1	51.8	52.0	53.8	54.4	54.7	55.7	55.0	56.1	58.5
cG	45.4	52.9	50.7	54.8	52.8	57.5	61.1	58.5	59.6	64.2	60.2	65.8	60.4	66.3	65.9

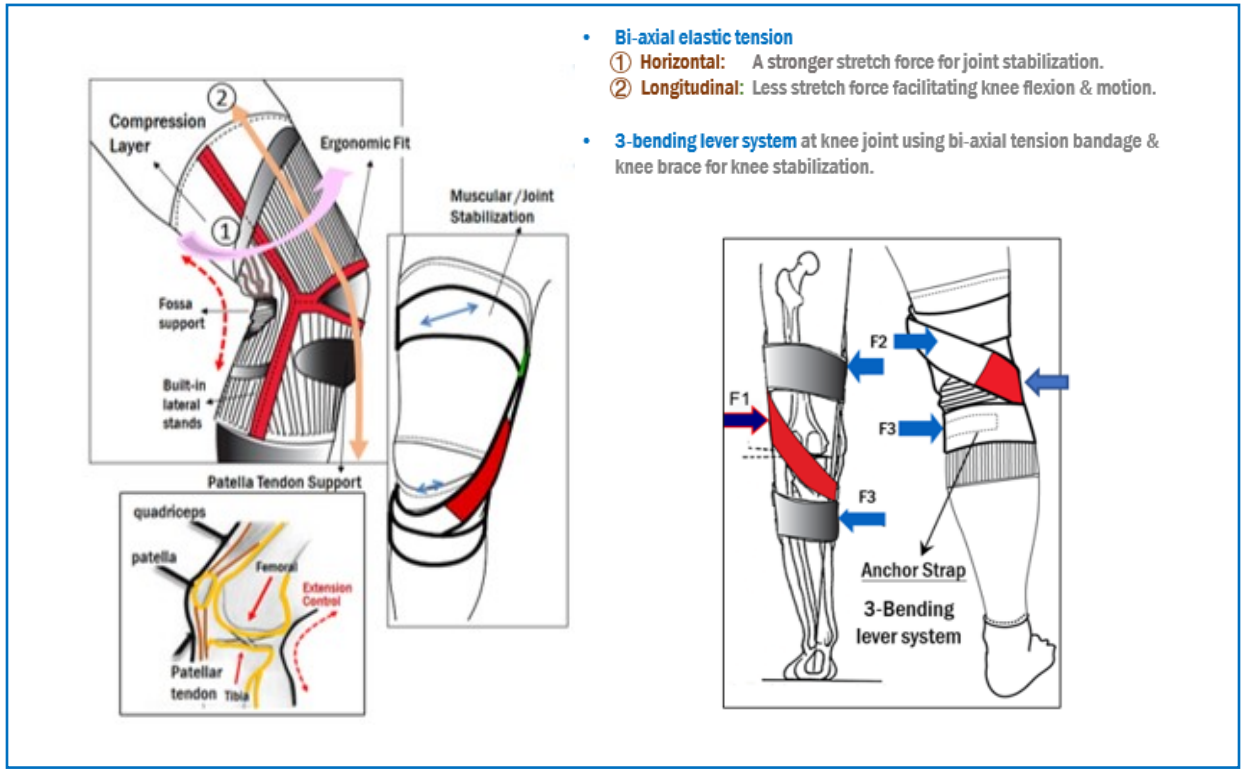
[a]The *Cir* value (cm) at *cE*, *cF*, *cG* positions with lower G_{EG}, that is, narrower openings at the thigh parts.
[b]The *Cir* value (cm) at *cE*, *cF*, *cG* positions with higher G_{EG}, that is, wider openings at the thigh parts.

Research Methods and Materials

Stage II: Design and development of compression orthesis.

Task 1: Biomechanical design of knee braces (KBs) for KP prevention and relief.

Knee brace: Bi-axial elastic tension & 3-bending lever system design of KBs.



Research Methods and Materials

Stage II: Design and development of compression orthesis.

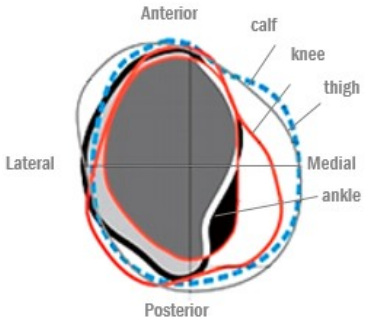
Task 1: Biomechanical design of compression stockings (CSs) for CVI prevention and treatment.

Compression stocking: "single & double progressive pressure" design of CSs.

Longitudinal: gradient pressure for counteracting the gravity force, and longer stretch for easily taking on and off in use.
Horizontal: shorter stretch to enhance muscular pumping action.

CS with single progressive pressure design for Asian body

CS with double progressive pressure design (biaxial tension control) with consideration of irregular lower limb structure



Irregular limb cross-sections

Research Methods and Materials

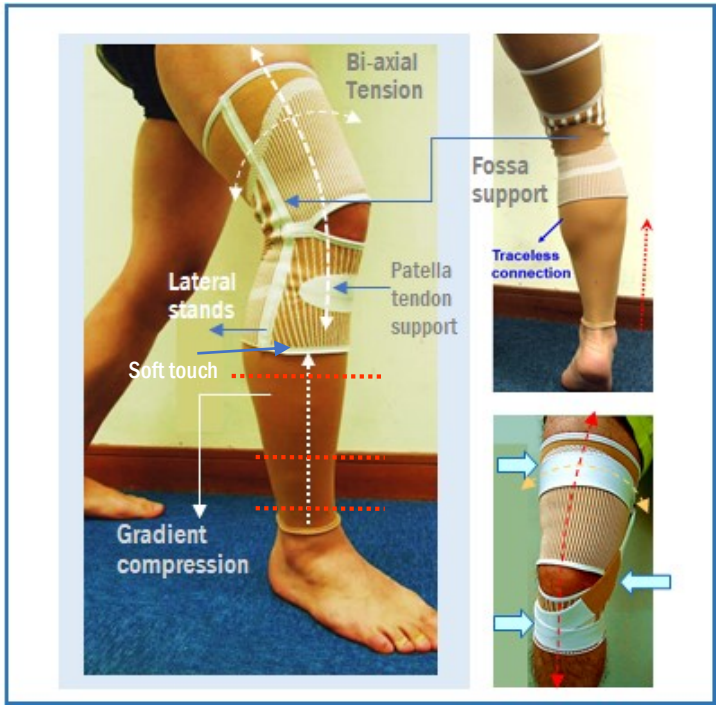
Stage II: Design and development of compression orthesis.

- Task 1: Biomechanical design of compression orthesis –"Leg Guarder Kit" for CVI-KP symptoms.

  1. Optimizing pressure profiles of compression orthesis.
  2. Avoiding tourniquet effect and local peak pressure (obstructing blood flow);
  3. Systematic management and control of muscular strain, knee joint activity, and blood circulation of lower limbs.

Features:

- Customized fit.
- Bi-axial elastic knitting layer for stabilizing knee joint and facilitating knee flexion.
- Seamless build-in patella tendon support.
- Lateral support stands and straps for enhanced knee joint stabilization.
- Stocking gradient compression facilitating the venous return and leg comfort.
- The kit can be used as one set, or independently used as knee brace or stocking in daily care.



Leg Guarder Kit

For lower limb venous-musculoskeletal system management

Research Methods and Materials

Stage II: Design and development of compression orthesis.

- Task 2: Digital knitting structure design & material testing.

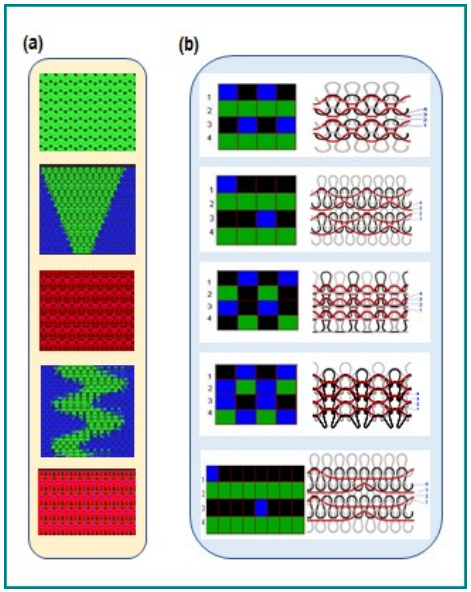
Incudoknit design

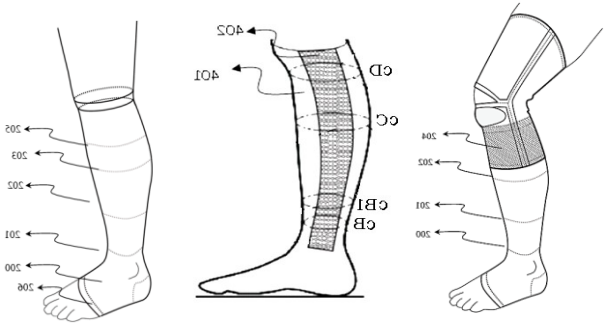
Compression fabrics exert an essential role in delivering controlled pressure dosages to counterbalance or compensate malfunction of the targeted component parts of the body.

(a) Incudoknit stitches consisted of the strategic 3D layout of ground and inlay threads through multi-step tension control to deliver the calibrated pressure dosages to the body.

(b) Hybrid weft knitting technologies for "Incudoknit" orthesis design:

- Seamless circular structure knitting
- Flat-bed structure knitting



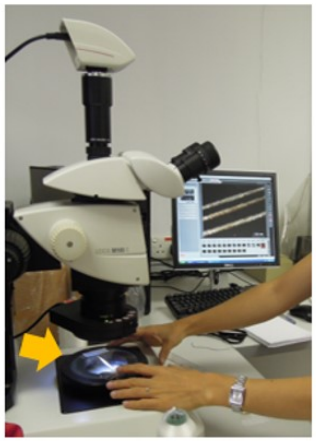


Research Methods and Materials

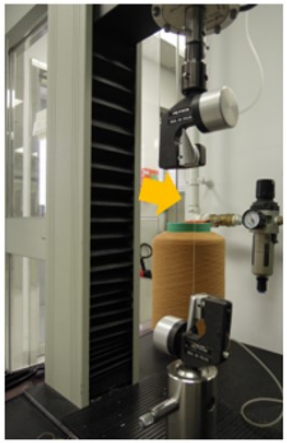
Stage II: Design and development of compression orthesis.

- Task 2: Digital knitting structural design & material testing for suitable quality fabric.

(a) Yarn microscopic structural test

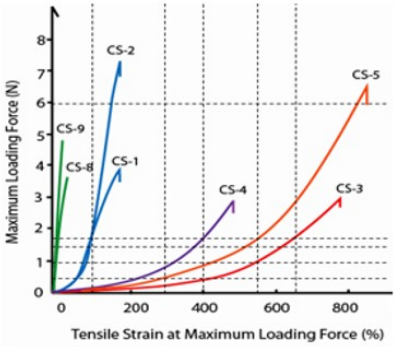


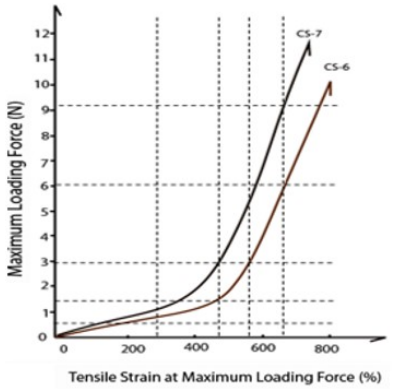
(b) Yarn tensile test



Medical-grade yarn selection

Instron 4411 tensile test
Standard Setting:
-200 mm gauge length
- 41b maximum load
- 300 mm/min speed



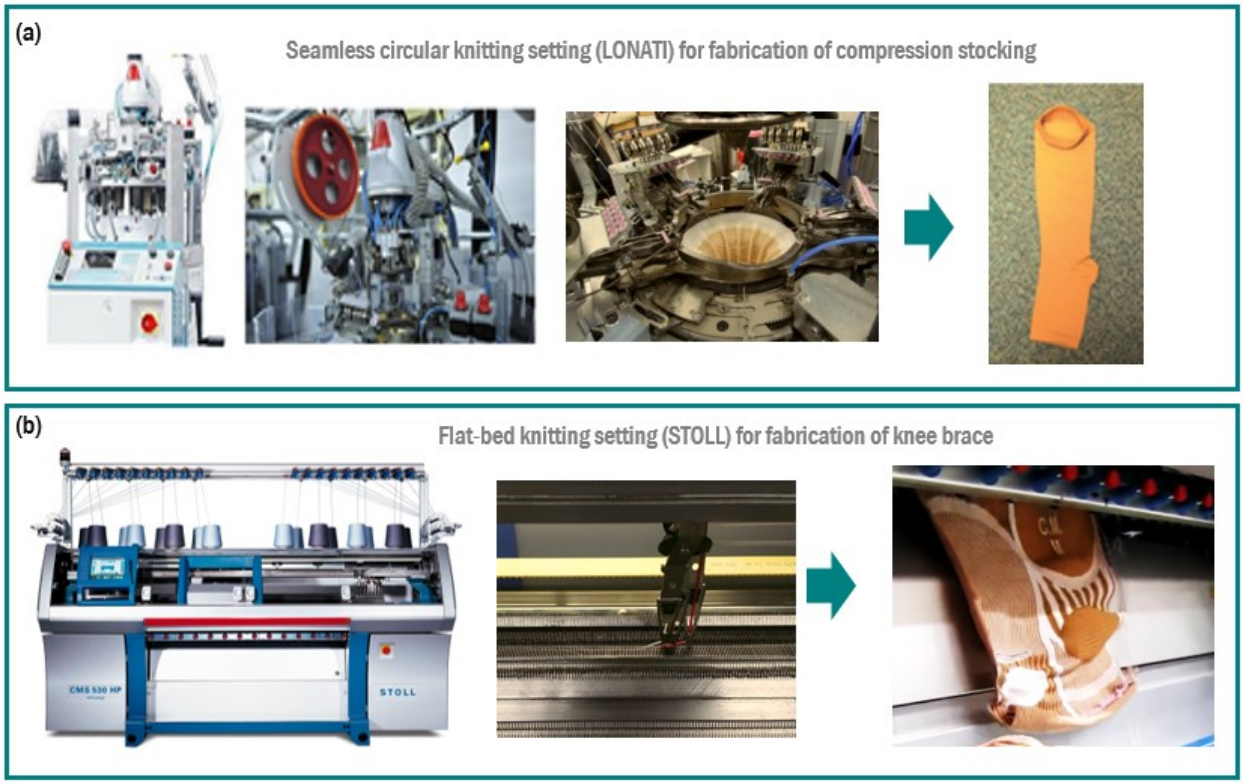


Strain-stress properties of the developed orthesis fabrics

Research Methods and Materials

Stage II: Design and development of compression orthesis.

- Task 3: Hybrid weft-knitting design and fabrication.



Research Methods and Materials

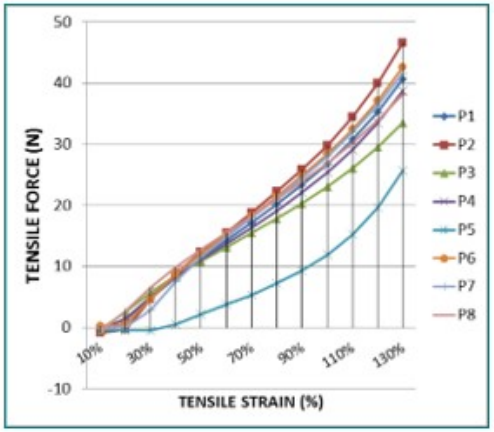
Stage II: Design and development of compression orthesis.

- Task 3: Hybrid weft-knitting design and fabrication: diverse compression orthesis fabrics.

Tensile test:

Test condition:

- Gauge length: 50 mm & 40 mm.
- Loading force (N) recorded at the 1st& 6th tensile cycles (300 mm/min) and following 10s holding.
- Stress decay (%) and inst. elastic recovery (%) were calculated.



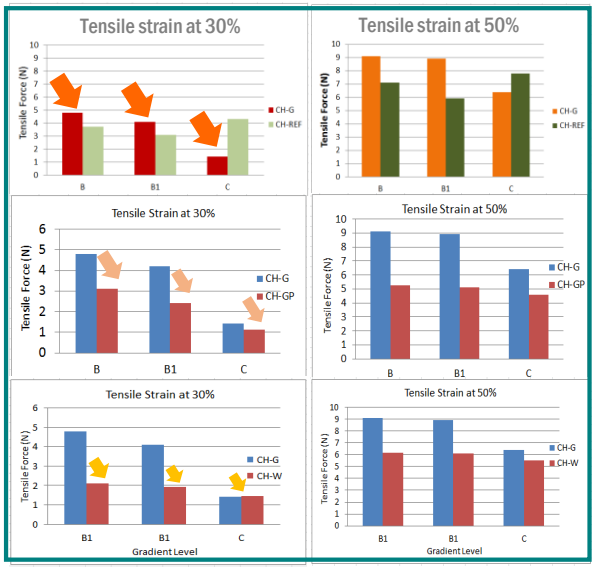
Research Methods and Materials

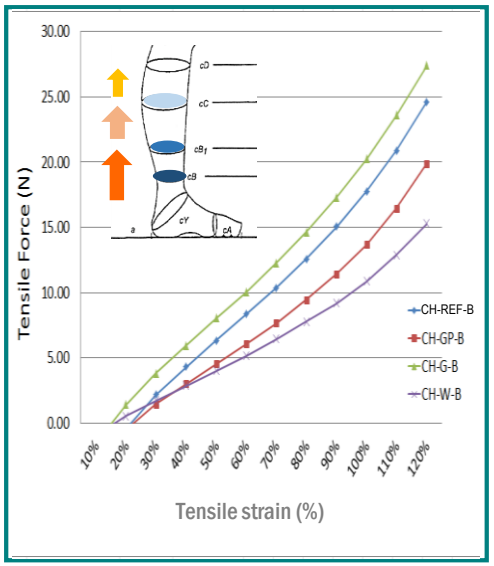
Stage II: Design and development of compression orthesis.

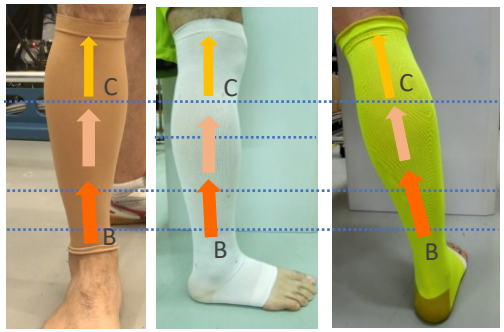
- Task 3: Hybrid weft-knitting design and fabrication: gradient compression stockings with optimized pressure profiles.

Progressive (gradient) tensile forces of stocking fabrics from the knee to the ankle: facilitate gradient pressure dosage delivery along the lower limb.

Progressive pressure gradient from the calf (C) to the ankle (B): counteract the gravity force and facilitate venous return.







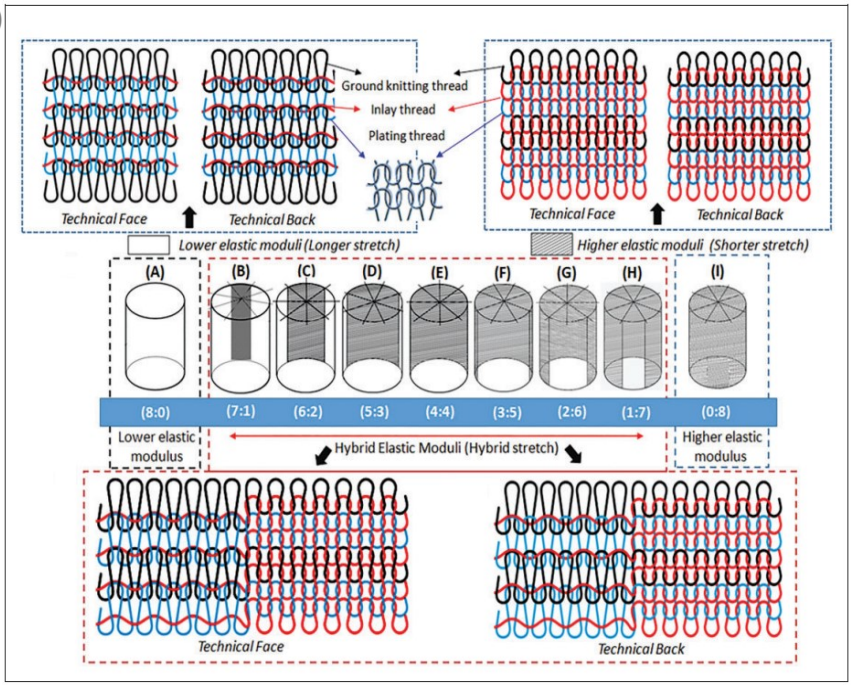
Research Methods and Materials

Stage II: Design and development of compression orthesis.

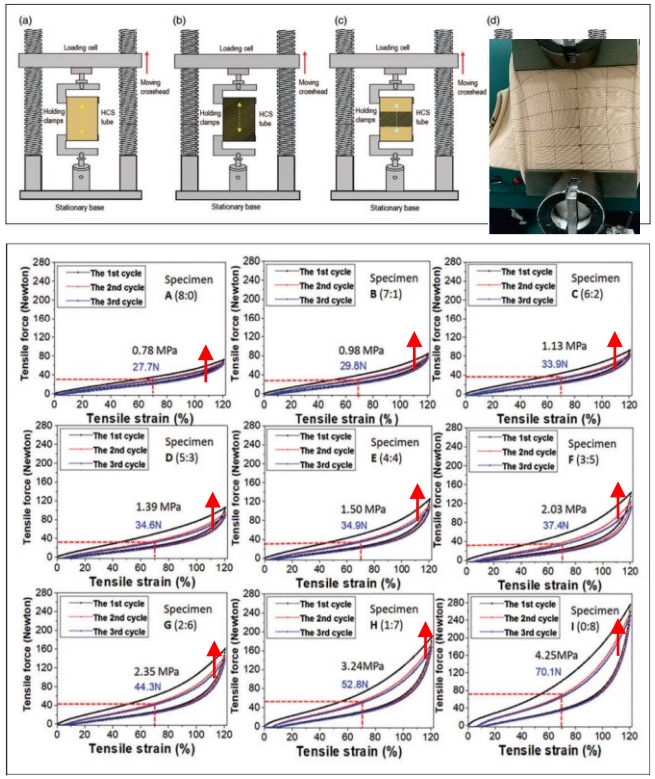
- Task 3: Hybrid weft-knitting design & fabrication: heterogeneous compression stockings with pressure reshaping capability.

Materials with the Incudoknit structures (a) and hybrid mechanical properties design (b).

(a)



(b)

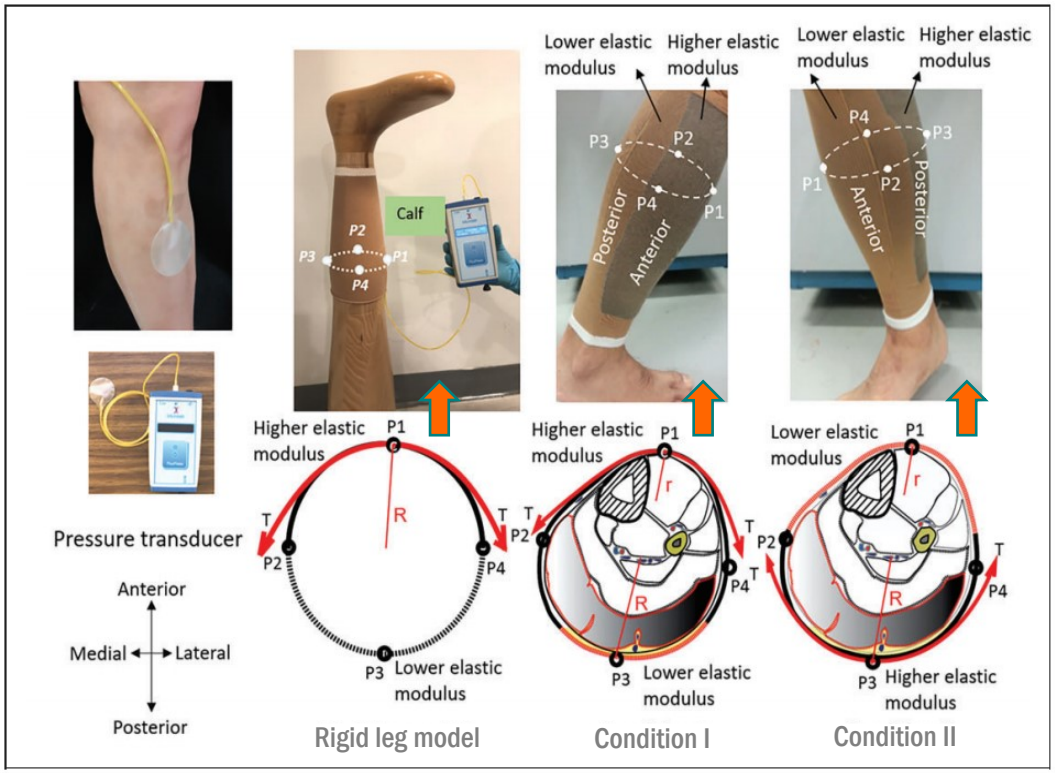


Research Methods and Materials

Stage II: Design and development of compression orthesis.

- Task 3: Hybrid weft-knitting design and fabrication: heterogeneous compression stockings.

In addition to the designed longitudinal gradient pressure, a horizontal progressive pressure profile from anterior to posterior calf was also designed, to augment muscular pumping action for improving venous return, and avoid peak pressure at anterior tibia for user comfort.



Two types of stiffness design were practiced:

Condition I:

- Panel with higher stiffness level set at anterior leg
- Panel with lower stiffness level set at posterior leg

Condition II:

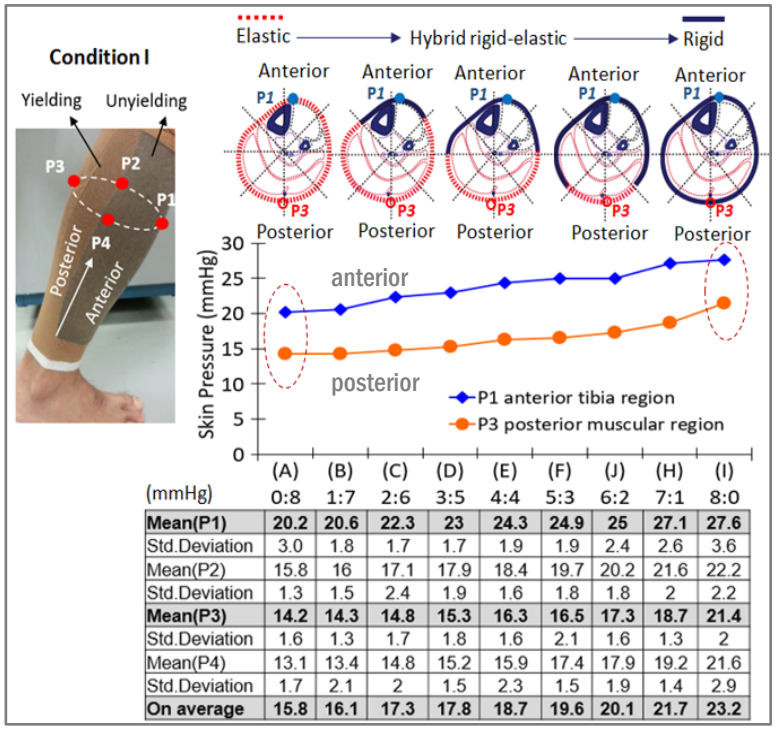
- Panel with lower stiffness level set at anterior leg
- Panel with higher stiffness level set at posterior leg

Research Methods and Materials

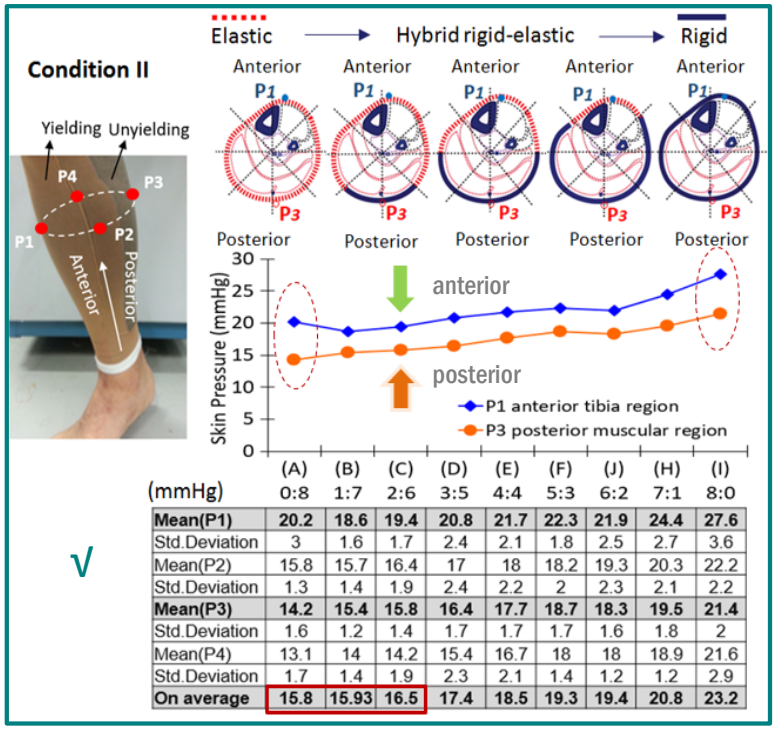
Stage II: Design and development of compression orthesis.

- Task 3: Hybrid weft-knitting design and fabrication: heterogeneous compression stockings.

- In condition II, the new HCSs with increased posterior skin pressure but reduced anterior pressure fulfils the expected pressure profiles.
- Therefore, condition II was adopted in new HCSs design for enhanced medical function and user comfort.



(mmHg)	(A) 0:8	(B) 1:7	(C) 2:6	(D) 3:5	(E) 4:4	(F) 5:3	(J) 6:2	(H) 7:1	(I) 8:0
Mean(P1)	**20.2**	**20.6**	**22.3**	**23**	**24.3**	**24.9**	**25**	**27.1**	**27.6**
Std.Deviation	3.0	1.8	1.7	1.7	1.9	1.9	2.4	2.6	3.6
Mean(P2)	15.8	16	17.1	17.9	18.4	19.7	20.2	21.6	22.2
Std.Deviation	1.3	1.5	2.4	1.9	1.6	1.8	1.8	2	2.2
Mean(P3)	**14.2**	**14.3**	**14.8**	**15.3**	**16.3**	**16.5**	**17.3**	**18.7**	**21.4**
Std.Deviation	1.6	1.3	1.7	1.8	1.6	2.1	1.6	1.3	2
Mean(P4)	13.1	13.4	14.8	15.2	15.9	17.4	17.9	19.2	21.6
Std.Deviation	1.7	2.1	2	1.5	2.3	1.5	1.9	1.4	2.9
On average	**15.8**	**16.1**	**17.3**	**17.8**	**18.7**	**19.6**	**20.1**	**21.7**	**23.2**

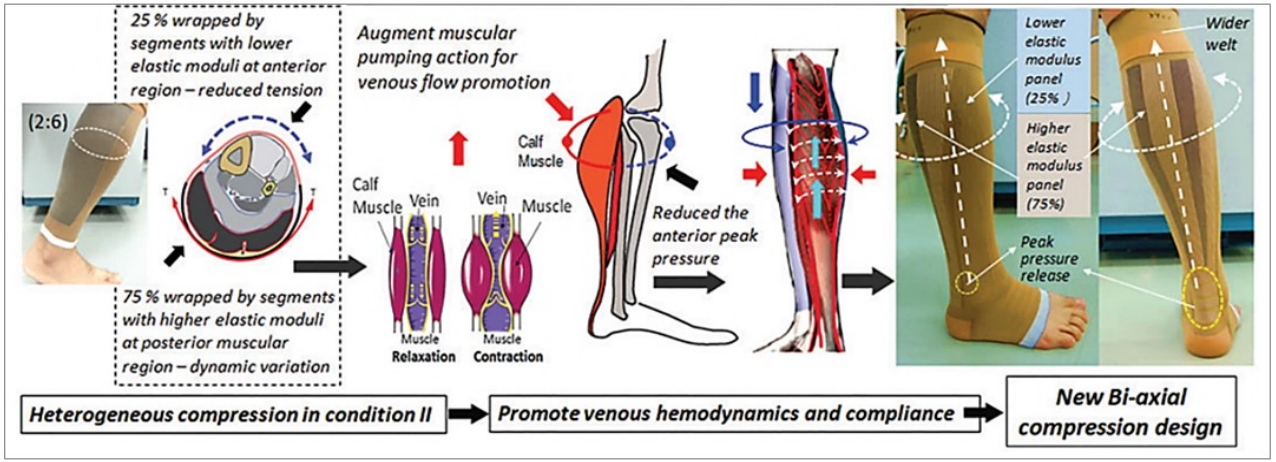


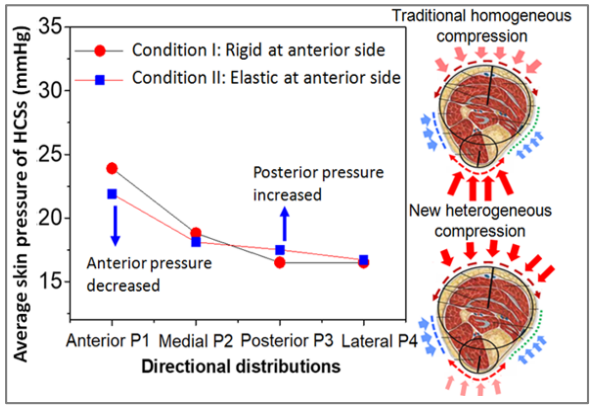
(mmHg)	(A) 0:8	(B) 1:7	(C) 2:6	(D) 3:5	(E) 4:4	(F) 5:3	(J) 6:2	(H) 7:1	(I) 8:0
Mean(P1)	**20.2**	**18.6**	**19.4**	**20.8**	**21.7**	**22.3**	**21.9**	**24.4**	**27.6**
Std.Deviation	3	1.6	1.7	2.4	2.1	1.8	2.5	2.7	3.6
Mean(P2)	15.8	15.7	16.4	17	18	18.2	19.3	20.3	22.2
Std.Deviation	1.3	1.4	1.9	2.4	2.2	2	2.3	2.1	2.2
Mean(P3)	**14.2**	**15.4**	**15.8**	**16.4**	**17.7**	**18.7**	**18.3**	**19.5**	**21.4**
Std.Deviation	1.6	1.2	1.4	1.7	1.7	1.7	1.6	1.8	2
Mean(P4)	13.1	14	14.2	15.4	16.7	18	18	18.9	21.6
Std.Deviation	1.7	1.4	1.9	2.3	2.1	1.4	1.2	1.2	2.9
On average	**15.8**	**15.93**	**16.5**	**17.4**	**18.5**	**19.3**	**19.4**	**20.8**	**23.2**

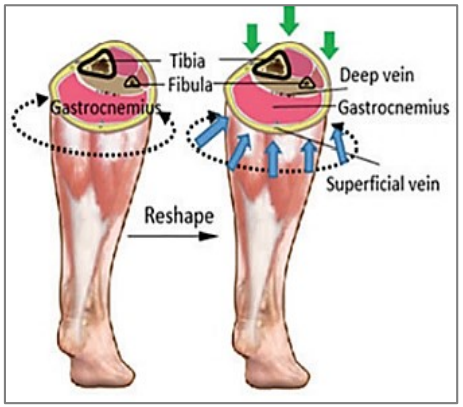
Research Methods and Materials

Stage II: Design and development of compression orthesis.

- Task 3: Hybrid weft-knitting design and fabrication: heterogeneous compression stockings.







Biomedical function of Bi-axial compression:

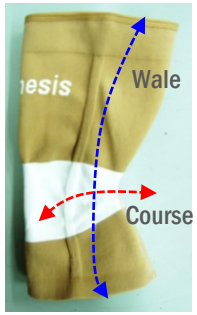
(1) **Horizontal:** reduced anterior peak pressure and increased posterior pressure for augmenting muscular pumping action.

(2) **Longitudinal:** gradient pressure for venous return.

Research Methods and Materials

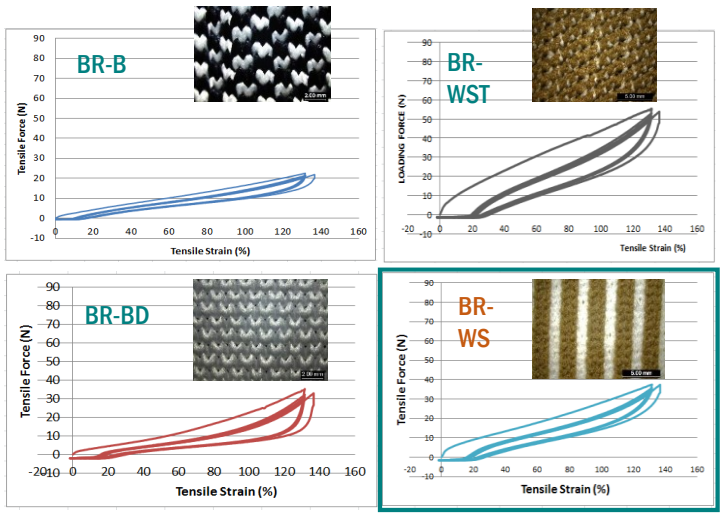
Stage II: Design and development of compression orthesis.

- Task 3: Hybrid weft-knitting setting and fabrication: knee braces.

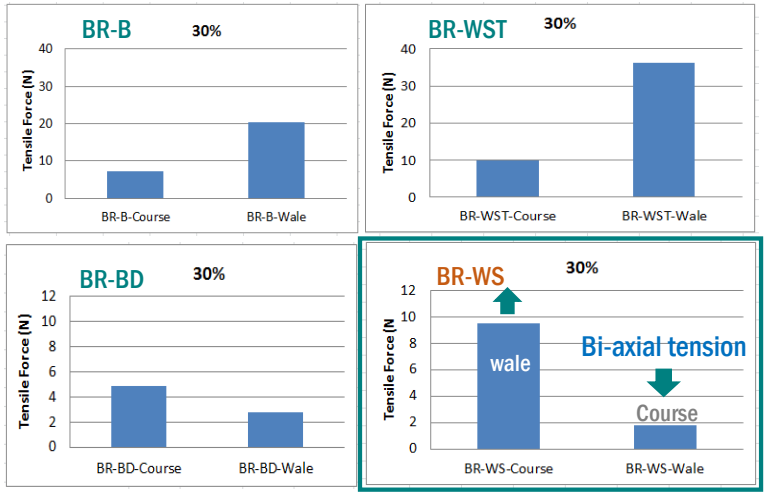


Bi-axial tension control: BR-WS fabric was defined (high recovery, distinct tensile forces in wale & course directions) as the most suitable fabric to stabilize knee joint & facilitate knee motion.

Tensile-strain test of different knitting structures in knee brace fabrics



Tensile-strain in wale & course directions among different knee brace fabrics

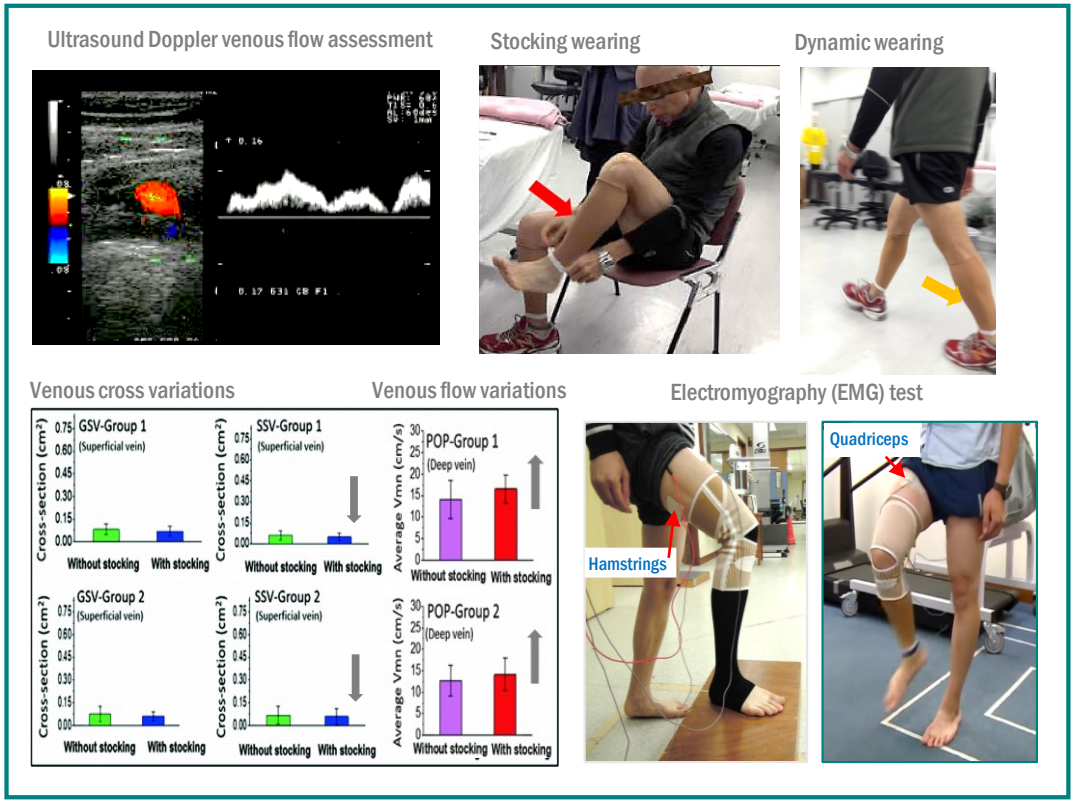


Research Methods and Materials

Stage III: Performance assessment of compression orthesis.

- **Task 1: Lab assessment of hemodynamics and muscular activities using new compression stocking and knee brace.**

75 min lab assessment: effects of CSs on venous anatomy and hemodynamics of lower limbs.



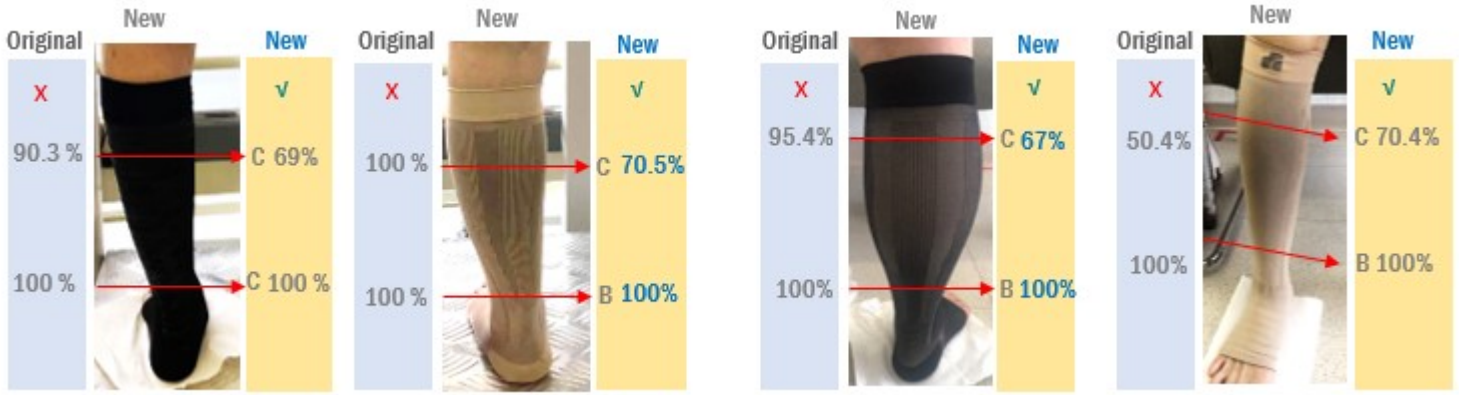
- 30 subjects (aged 39-79 yrs) participated in the assessment.
- The venous flow velocity of the tested deep veins (POP) increased by approx. 4.0%-19.6% by using the designed CSs.
- The venous cross-sections of GSV and SSV reduced by apparox.13%–16% by using the designed CSs.
- The developed KBs reduced the knee loading force by decreasing muscular cocontraction levels. This reduction mitigates overstress in the ligaments supporting the knee joint and decelerates the induction of KP by osteoarthritis progress.

Research Methods and Materials

Stage III: Performance assessment of compression orthesis.

- Task 1: Lab assessment of hemodynamics and muscular activities using new compression stocking and knee brace.

  - Sustained the pressure dosages (15-25 mmHg) for at least 3-month (12 weeks) after daily washing.
  - Improved fitting for users with different body shapes.
  - Progressive pressure proportions of calf/ankle (C:B) can be optimized to 65%-75% (C) at the calf and 100% (B) at the ankle for the individuals, which fulfilled the requirements of gradient compression therapy.



Research Methods and Materials

Stage III: Performance assessment of compression orthesis.

- Task 2: Comfort and clinical surveys on the developed compression orthesis.

12 weeks of public trials: study on the effects of the developed compression stockings on leg health and comfort among 150+ subjects.

- 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 Community care services

東華三院 Tung Wah Group of Hospitals

94%-96% of the investigated users indicated that the developed compression orthesis (stockings) were easier to put on and take off, and 93% of the users indicated wearing comfort in daily use.

Research Methods and Materials

Stage-IV: User feedback analysis and design optimization.

150+ Asian users from public society participated in the wearing comfort survey.

Helen is a marathon runner.
She indicated that, "*The use of new compression orthesis allow me no stop in the middle way, and provided the protection to my leg, and improved running endurance and efficiency*."

Special Report by Radio Television of Hong Kong (RTHK) in programme "Doctor and You" http://qrgo.page.link/4LSsB

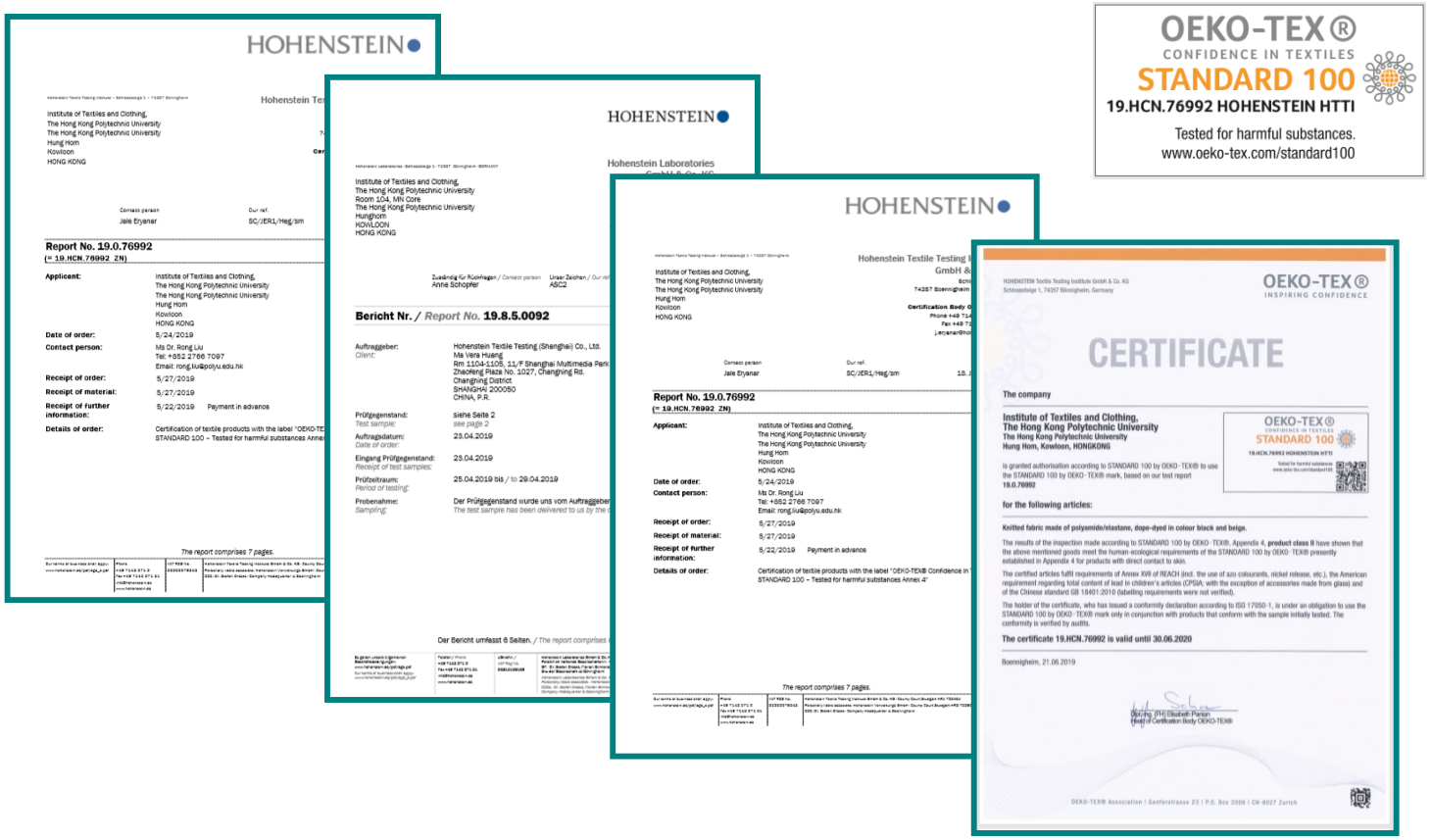
Mr. Yuan suffers from knee pain. He commented that "*I felt an improved comfort and knee stability (support) using the developed modern compression orthesis in walking*".

New compression stockings with fitting size were used by Pingpang athletes and coach of Hong Kong Sports Institute in training.

Research Methods and Materials

Stage-IV: User feedback analysis and design optimization.

Safety test: the developed compression orthesis fabrics has passed the test of cytotoxicity, sensitization and irritation test, and received safety certificate OEKO-TEX Standard 100.



Research Conclusions

A modern compression orthosis specifically adapted to Asian users was designed and developed. Compared with other existing orthoses, this novel orthosis offers comfort, hemodynamic efficacy, and knee pain (KP) relief to users. Double progressive compression stockings (CSs) and biaxial-tension knee braces were strategically designed according to the evidence from a clinical survey, large-scale anthropometric study, and biomechanical study.

The study results demonstrated that the developed compression orthosis provided support to the knee joint and alleviated KP. The newly developed CSs enhanced venous flow in the deep veins by approximately 4.0%–19.6%. Moreover, 93% of users reported that the new stockings were comfortable, and 94%–96% of users indicated that the new orthesis were easier to take on and off compared with previous ones.

Our modern compression orthosis is a promising physiotherapeutic tool that can enhance people's lower limb health, physical function, and self-management in daily life.

Dissemination and distribution of outcomes

10 publications, 4 patents, 3 exhibitions, 1 design award, 2 videos, 7 media reports, 4 invited talk, 1 industrial consultancy project, 1 national industry standard, 1 new business, 600+ sets of compression orthesis (stockings, brace, kit), and 300+ benefited Asian users.

Publication (10)

(1) 2019 XB WU, **R LIU***. Modern textile-based compression device for improving venous haemodynamics of lower extremities. In: Goonetilleke R., Karwowski W. (eds) Advances in Physical Ergonomics and Human Factors. Advances in Intelligent Systems and Computing, vol 967. Springer, Cham. https://qrgo.page.link/Mf1y5

(2) 2018 **R LIU***, X GUO, QJ PENG, L ZHANG, TT LAO, T LITTLE, JD LIU, E CHAN. Stratified body shape-driven sizing system via three-dimensional digital anthropometry for compression textiles of lower extremities. Textile Research Journal 2018, 88(18): 2055-2075, DOI: 10.1177/0040517517715094. https://qrgo.page.link/XM4Xu

(3) 2018 **R LIU*,** TT LAO, T LITTLE, XB WU, X KE. Can heterogeneous compression textile design reshape skin pressures? A fundamental study. Textile Research Journal 2018:88(17):1915-1930. https://qrgo.page.link/Qykds

(4) 2018 **R LIU***. Pressure reconstruction by heterogeneous compression textiles. Veins and Lymphatics 2018; 7:7621:56-58. https://qrgo.page.link/XUSZz

(5) 2017 **R LIU***, X GUO, TT LAO, T LITTLE. A critical review on compression textiles for compression therapy: Textile-based compression interventions for chronic venous insufficiency. Textile Research Journal 2017; 87(9) 1121-1141. https://qrgo.page.link/ap195

Dissemination and distribution of outcomes

Publication (10)

(6) 2017 **R LIU***. Advanced compression textiles for physiotherapy and performance enhancement. Asia and Africa Science Platform Program Conference. Kyoto Institute of Technology. 16th-17th.Mar., 2017, Kyoto, Japan. https://qrgo.page.link/LNCps

(7) 2016 **R LIU***, X GUO. Reshaped pressure mode by novel compression legwear to avoid peak focal pressure and raise muscular pumping action. Bubai International Healthcare Summit-International Diabetes and Obesity Congress-2016. Subhadra Healthcare, 18-20th. Oct., 2016, Dubai.

(8) 2016 X GUO*, **R LIU**. Compression knee orthosis can decrease muscle activation and co-contraction of quadriceps and hamstring muscles during walking and step activities. Bubai Healthcare Summit-International Diabetes and Obesity Congress-2016. Subhadra Healthcare, 18-20th. Oct., 2016, Dubai.

(9) 2013 **R LIU***, TT LAO, SX WANG. Impact of weft laid-in structural knitting design on fabric tension behavior and Interfacial pressure performances of circular knits, Journal of Engineered Fibers and Fabrics 2013; 8(38): 83-90.

(10) 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. https://qrgo.page.link/8j4aJ

Dissemination and distribution of outcomes

Patents (4)

(1) 2017 **R LIU**, X GUO, TT LAO, T LITTLE, D TAND, XY WANG. A type of compression orthesis (CN205884729 U), State Intellectual Property Office of the P.R.C.,2nd.Nov.2016.

(2) 2016 **R LIU**, X GUO, TT LAO, T LITTLE, D TANG, XY WANG. Knee brace (20163054799.2), State Intellectual Property Office of the P.R.C.,26th.July.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.

(4) 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.

Dissemination and distribution of outcomes

International Exhibition (3)

(1) 2016 The developed prototypes “leg guarder kit” were displayed at the 44th International Exhibition of Inventions of Geneva, Switzerland, April 2016. https://qrgo.page.link/q2v5v

(2) 2014 The developed “compression stocking products” were displayed in China Yiwu International Exhibition on Textile Machinery, Yiwu International Expo Centre, China, June 2014. https://qrgo.page.link/bAa7s

(3) 2014 The developed compression hosieries products were displayed as “Medical Device” in the 12th Chinese Vascular Surgery Congress, 21-24th, Aug., Shanghai, 2014.

The 44th International Exhibition of Inventions Geneva (13th -17th April 2016)

This is the world’s unique annual exhibition. It is under the patronage of the Swiss Federal Government, the State, the City of Geneva and of the World Intellectual Property Organization – WIPO. There were 1000 new inventions and products, 752 exhibitors from 48 countries, 59,000 visitors from all 5 continents. This support testifies to the usefulness and quality of the event, now acknowledged as the most important exhibition of inventions anywhere today. It is also the most international, with the participation of more than 48 countries.

Dissemination and distribution of outcomes

Award (1)

Year	Events
(1) 2016	The developed “Leg Guarder Kit” was awarded “Bronze Medal” in the 44th International Exhibition of Inventions of Geneva, Switzerland, April 2016, https://qrgo.page.link/oYhbE

Dissemination and distribution of outcomes

Invited public talk (4)

Year	Events
(1) 2017	**R LIU**. Novel Heterogeneous stiffness for dynamic compression reconstruction. International Compression Club Annual Conference, 9th.Dec.2017, Paris, France. https://qrgo.page.link/1AqcF
(2) 2017	**R LIU**. "Advanced Compression Textiles for Physiotherapy and Performance Enhancement", at "Establishment of Collaboration Research for 'Newo-Fiber Technology' in Asia and Africa + Seminar Series 10", Kyoto Institute of Technology, Japan, 16-18th, Mar.2017. https://qrgo.page.link/LNCps
(3) 2016	**R LIU**. "Innovative Tailor-made Compression Orthesis", at "Huaxia Innovative Medical Device Summit", Prices of Wales Hospital, Hong Kong, 28th.Oct.2016.
(4) 2014	**R LIU**. "Application of Compression Garments in Treatment of Vascular Diseases". The 12th Chinese Vascular Surgery Congress, Shanghai, China, 21-24th, Aug., 2014.

Dissemination and distribution of outcomes

National Industrial standard (1)

Year	Events
2014	National Industrial standard on “Healthcare Compression Hosiery” (CAS 201-2014). Liu’s research has underpinned the development of the 1st China national industrial standard “Healthcare Compression Hosiery”. The standard has been effectively released and implemented since 2014. This standard not only benefits product quality control and use safety, but has also facilitated industrial transformation from low-end to high-end value-added hosiery products by providing companies with clear standards to meet.

Dissemination and distribution of outcomes

Videos (2) and Media Interview (7)

Year	Events
2016	The "Innovation of Customized Compression Orthesis" was broadcasted by TV programme "Doctor and You" of Radio Television of Hong Kong (RTHK) on 26th.Sept.2017. https://qrgo.page.link/4LSsB
2016	Special report by Institute for Entrepreneurship of the Hong Kong Polytechnic University, Technology Frontier: Leg Guarder Kit, Custom-made leg support that prevents and treats varicose veins and knee pain https://qrgo.page.link/SEzKN
2016	Media Interview The developed modern integrative compression orthesis was reported by medial interview. (1) ON.CC (video) http://goo.gl/QBcAJZ (2) Oriental Daily https://qrgo.page.link/eEViK (3) HK01 http://goo.gl/OzNMUp (4) Sina HK http://goo.gl/TTWcF1 (5) Sing Tao Headline https://qrgo.page.link/ky8up (6) HKCD https://qrgo.page.link/PSdgA (7) RTHK https://qrgo.page.link/4LSsB

Dissemination and distribution of outcomes

Industrial Consultancy Project (1)

2017-2018

Dr. LIU, as Project Manager & Consultant, received a Funded Consultancy Project entitled “Technical Guidance and Professional Advice on Product Performance of Customized Compression Knee Brace and Compression Hosiery” (P16-0342).

This Consultancy Project was funded by,

Technology and Consultancy Company Ltd. of the Hong Kong Polytechnic University (http://www.ptec.com.hk/) and Chemtax Industrial Co. Ltd (http://www.chemtax.com/).

Dissemination and distribution of outcomes

Commercialization

Year	Events
2015-2019	(1) The research underpinned a new business: Healthcare Pathways Group (HPG). The HPG has commercialized the developed compression orthesis in 2018 (compression stockings and knee brace).
	(2) End users included marathon athletes, stroke suffers, teachers, nursing staff, electronics, and elderly people, etc (refer to the Programme “Doctor & You). https://qrgo.page.link/4LSsB
	(3) The developed compression stockings have been used by Pingpang coach and athletes of the Hong Kong Sports Institute in training.

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2) Shammeri OA, Aihamdan N and Ai-hothaly B. Chronic venous insufficiency: prevalence and effect of compression stockings. Int J Health Sci 2014; 8: 231–236.
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4) Nguyen USD, Zhang YQ, Zhu YY, et al. Increasing prevalence of knee pain and symptomatic knee osteoarthritis. Ann Intern Med 2011:155(11): 725-732.
5) Peat G, McCarney R, Croft P. Knee pain and osteoarthritis in older adults: a review of community burden and current use of primary health care. Ann Rheum Dis 2001;60:91-97.
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10) Liu R. Thesis. Biomechanical efficacy of knee bracing on joint kinetics and kinematics, postural steadiness and wearing perception. The Hong Kong Polytechnic University, 2015.

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