Medical Engineering and Physics 50 (2017) 65–74

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Motorized adaptive compression system for enhancing venous return: A feasibility study on healthy individuals

Mahan Rahimi[a], Andrew P. Blaber[b], Carlo Menon[a,*]

[a] MENRVA Research Group, Schools of Mechatronic Systems Engineering and Engineering Science, Simon Fraser University, Metro Vancouver, BC V3T 0A3, Canada

[b] Aerospace Physiology Laboratory, Department of Biomedical Physiology and Kinesiology, Simon Fraser University, Burnaby, BC V5A 1S6, Canada

ARTICLE INFO

Article history:
Received 11 April 2017
Revised 18 August 2017
Accepted 4 October 2017

Keywords:
Venous insufficiency
Compression therapy
Wearable technology
Adaptive compression system
Force-sensing resistor
Lower body negative pressure

ABSTRACT

Notwithstanding the extensive use of conventional compression devices in managing venous disorders, these modalities have shortages that diminish their treatment efficacy and lessen patient adherence to therapy. The purpose of this study was to develop an improved compression system that eliminates the flaws of the existing devices. A motorized bandage was designed that takes advantage of continuous feedback from force-sensing resistors to apply reproducible, controlled pressure on the lower extremities. The performance of the device in enhancing venous return was explored in a pilot test on 11 healthy participants, wherein graded lower body negative pressure was employed as a surrogate of passive standing. Each subject underwent two experiments; with and without pressure application over the calves. A two-way repeated-measures analysis of variance revealed a significant difference in the mean hemodynamic responses when the compression bandage was in action ($p < .05$). Specifically, a meaningful increase was observed in mean arterial pressure by 5%, diastolic blood pressure by 8% and left ventricular ejection time by 4%; and a significant decrease of 5% and 6% was noticed in heart rate and pulse pressure, respectively. These results demonstrate the capability of the designed system in attenuating the imposed orthostatic stress on cardiovascular system.

1. Introduction

Compression therapy, which refers to the benefits gained from exertion of external pressure to the body, has grown in different medical and non-medical fields. It provides a means to control, treat, and prevent a variety of conditions, including, but not limited to, orthostatic intolerance [1,2], hemorrhage [3,4], burn scars [5,6], post-surgical operation [7–9], athletic enhancement [10–12], and aviation and post-spaceflight complications [13–15]. In addition to the foregoing, chronic venous disease (CVD) of the lower extremities is one of the most common indications for compression therapy [16]. In the presence of any deficiency in the normal, concomitant function of calf muscle pump and one-way venous valves, which serve to counteract gravitational forces and direct blood flow to the heart [17], the efforts towards emptying the veins fail, resulting in retrograde blood flow, blood accumulation, and progressive complications due to elevated pressure in the veins, especially during locomotory activities (i.e. walking and running) [18–21]. Unabated venous hypertension can be accompanied with significant discomfort and troublesome pathologies that negatively affect the quality of life, including varicose veins, excessive leg swelling, heaviness in the legs, pain, ulceration, and hypotension-induced fainting to name a few. These abnormalities in the skin and subcutaneous tissues of the lower extremities are referred to clinically as chronic venous disease [22–24]. CVD is a high-prevalence and debilitating medical condition among the adult population [18,25], especially the elderly, pregnant women and spinal cord injury patients. In addition to reducing life quality and causing social impairment, CVD can be very costly to the health care system due to prevalence, morbidity, and chronicity [25–27], necessitating taking action towards its management.

Compression therapy is established as the mainstay for treatment of venous insufficiency and the associated complications, and its efficacious role in management of venous disorders has been the subject of numerous studies [28–31]. Circumferential compression aims to reverse the detrimental effects of venous hypertension via increasing the pressure on the skin and underlying structures, thereby improving blood circulation [19]. Bandages, stockings, and mechanical pumps are among the popular remedies to tackle venous insufficiency. Although being used extensively, compression devices, in their current form, have some drawbacks and limitations. Mechanical pumps are usually bulky and do not allow

* Corresponding author.
E-mail address: cmenon@sfu.ca (C. Menon).

https://doi.org/10.1016/j.medengphy.2017.10.005
1350-4533/

Table 1
Comparison of current compression therapy modalities[a].

Type		Advantage	Disadvantage	Example
(1) Bandage / Wrap	Inelastic	• High working pressure • Well-tolerated in rest • Ambulatory use	• Trained bandager • Non-adaptive to changes • Slippage • Frequent re-application • Pressure loss over time	• Zinc paste (Unna's boot)
	Short-stretch single-layer	• High working pressure • Well-tolerated in rest • Ambulatory use	• Trained bandager • Non-adaptive to changes • Slippage • Frequent re-application • Pressure loss over time [37]	• Lastolan® • Acrylastic® • Comprilan
	Long-stretch single-layer	• Self-applicable [38] • High working pressure • Adaptive to changes • Little pressure loss over time • Ambulatory use	• High resting pressure • Intolerable during rest	• Tensopress® • Setopress® • Surepress
	Multi-component	• High working pressure • Well-tolerated in rest • Adaptive to changes • Ambulatory use	• Trained bandager	• Actico® • Profore© • Urgo KTwo©
(2) Stocking		• Self-applicable • Ambulatory use • Possibility of daily skin care	• Difficult to don • Non-adaptive to changes • Low efficacy in improving venous hemodynamics [38] • Fitting problems [26]	Various brands: • Jobst • Mediven • Sigvaris
(3) Adjustable	Velcro device	• Self-applicable • Self-adjustable • Ambulatory use • Possibility of daily skin care	• Unappealing appearance compared to stockings	• CircAid©
(4) Mechanical pump	Pneumatic	• Self-applicable • Self-adjustable • Possibility of daily skin care	• Bulky • Non-ambulatory use • Need for air pump • Difficulty of portability	• VenaPro™ • Medshoola™
	Hybrid	• Self-applicable • Self-adjustable • Ambulatory use • Adaptive to changes • Possibility of daily skin care	• Limited pressure range • Bulky	• ACTitouch®
	Non-pneumatic	• Self-applicable • Self-adjustable • Ambulatory use • Possibility of daily skin care	• Limited to peristaltic mode • Bulky	• Venowave

[a] Adapted from [16,39]

for ambulatory use [16]. Bandages do not serve to sustain pressure over time, necessitating frequent re-applications, and putting them on correctly is highly clinician dependent [29]. Compression hosiery, whose efficacy has been proven to change with anthropometric variables, are difficult to don, and neither these products nor medical wraps are beneficial during passive orthostasis [1] that can be attributed to their incapability in generating cyclical pressure gradient, as experienced during gait, and compensating for the lack of calf muscle pump activation [32]. Also, exertion of recommended pressure levels and their sustenance is of utmost importance for successful treatment, entailing the need for monitoring and controlling pressure beneath the compression garments [33]. However, sub-bandage pressure, which is determined by garment properties, geometry of the limb, skill of the operator, and physical activities and posture of the user [29,34], generally is not measured by the clinicians, and most of the existing compression therapy modalities are not equipped with any technology to continuously sense interface pressure. The health care practitioners count on their own experience while applying compression bandages, and the manufacturers' listed class of compression when prescribing compression hosiery [35,36]. When the recipients of compression products are discharged from medical centers, it is not feasible to assess the alterations in sub-bandage pressure that might occur as a consequence of movements and changing physiological conditions of the lower extremities, such as swelling reduction. The shortcomings of the existing compression systems attenuate the optimal performance of these devices and reduces their efficacy. Different types of the current compression therapy modalities, along with their advantages and disadvantage are summarized in Table 1.

All these reasons together served as a compelling demand for this study to design, fabricate, and evaluate a novel smart pressure garment—incorporating sensing, control, and actuation—that eliminates the aforesaid problems to the greatest extent possible. Herein, a wearable adaptive compression system (ACS) with a lace-driven actuation mechanism is proposed that can deliver different pressure types and can be used during stasis and ambulation. It is basically a wearable garment, with a motorized lacing system coupled to it, in which rotation of a geared motor is exploited to tighten and loosen a piece of fabric for delivering pressure in sustained and intermittent modes. The ACS is equipped with flexible force-sensing resistors (FSRs®) that are used to measure the exerted pressure on the skin. The interface pressure feedback from the FSRs® is beneficial not only in generating reproducible, controlled compression levels, but also in making the device adaptive to physiological changes of the legs.