Compression under pressure: physiological and methodological factors influencing the effect of compression garments on running economy

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ABSTRACT

Evidence for the effects of compression garments on sports performance and physiological responses to dynamic exercise remains equivocal. Contradictory findings within the sporting literature are confounded by methodological heterogeneity in terms of; intensity and modality of exercise, type of garment worn, and the interface pressure produced by the garment. The interface pressure applied by compression clothing is an important measure in evaluating the bio-physical impact of compression. Interface pressure values obtained *in vivo* with two portable pressure devices (PicoPress and Kikuhime) were compared against a reference standard (HOSY). The PicoPress satisfied the *a priori* thresholds for acceptable validity at the posterior and lateral orientation with calf stockings and tights, confirming its future use to assess interface pressure. A small, *likely beneficial* improvement in running economy was observed with correctly fitted (95%:5%:0%; η^2 = 0.55) but not oversized compression tights, indicating that a certain level of interface pressure is required.

Compression tights improved running economy only at higher relative exercise intensities (77.7 - 91.5% $\dot{V}O_{2max}$). The absence of any improvement at lower intensities (67.1 - 77.6 % $\dot{V}O_{2max}$) suggest that changes in running economy from compression are dependent on relative exercise intensity when $\dot{V}O_{2max}$ (%) is used as an anchor of exercise intensity.

Comparing measures from two portable, wireless near-infrared spectroscopy (NIRS) devices (PortaMon and MOXY) we found that the low-cost and light-weight MOXY device gave tissue oxygen saturation values at rest and during exercise that were physiologically credible and suitable for future research. Compression tights did affect ground contact time but not tissue oxygen saturation, cardiovascular or other kinematic parameters during running at intensities equivalent to long-distance race speed. Compression tights can produce small improvements in running economy, but effects are restricted to higher intensity exercise and appear dependent on garment interface pressure. It remains unlikely that this small positive effect on running economy, in very specific conditions, is enough to result in a meaningful impact on running performance.

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PREFACE

The work presented in this thesis has been peer reviewed as follows;

Peer reviewed publications

McManus, C., Collison, J., Cooper, C (2018) Performance comparison of the MOXY and PortaMon near-infrared spectroscopy muscle oximeters at rest and during exercise. *Journal of Biomedical Optics*, 12 (01):1

McManus, C., Venkatraman, P., Sandercock, G (2020) The measurement of interface pressure applied by sports compression garments: a comparative study of two portable devices. *Measurement*, 1;156:107592.

Conference presentations

McManus, C (2019) The measurement of interface pressure applied by sports compression garments: a comparative study of two portable devices (Oral presentation). European Wound Management Association, Gothenburg,

McManus, C (2015) Lower body compression tights elicit a practically significant benefit on sub-maximal running economy (Poster presentation). British Association of Sport & Exercise Sciences, St Georges Park.

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ABBREVIATIONS

ANOVA – analysis of variance

AROM – active range of motion

ATT – adipose tissue thickness

AUC – area under the curve

BF – breathing frequency

CI – confidence interval

CG – compression garment

CHO_{ox} - carbohydrate oxidation

CV – coefficient of variation

ES – effect size

FAT_{ox} – fat oxidation

GCT – ground contact time

HHb - deoxyhaemoglobin

HR – heart rate

Hz - hertz

IP – interface pressure

J – Youden index

La^- - blood lactate

LED – light emitting diode

LIST – Loughborough intermittent shuttle test

mmHg – millimetres of mercury

MVC - maximal voluntary contraction

N - newtons

NIRS – near-infrared spectroscopy

O_2Hb – oxyhaemoglobin

Pa - pascals

RE – running economy

RER – respiratory exchange ratio

ROC – receiver operating characteristic

RPE – rating of perceived exertion

SD - standard deviation

SEM -standard error of the mean

SmO_2 – saturated muscle oxygenation

SR – spatial resolution

SRS – spatially resolved spectroscopy

TE – typical error

tHb – total haemoglobin

TSI – tissue saturation index

T_{sk} – skin temperature

USG – urine specific gravity

VE – minute ventilation

$\dot{V}CO_2$ - volume of expired carbon dioxide

VL - vastus lateralis

$\dot{V}O_2$ – volume of oxygen consumption

$\dot{V}O_{2max}$ - maximum volume of oxygen consumption

$v\dot{V}O_{2max}$ - velocity at maximum volume of oxygen consumption

W - watts

1 Introduction

Compression garments apply mechanical pressure to the underlying surface and produce a range of physiological responses. In a clinical setting, the aim of compression is to augment venous and arterial blood flow and limit the physical space available for swelling to occur. This augmented physiological response observed at rest is attractive to the athletic population; however, findings from non-active populations are often inappropriately extrapolated into the sporting domain. Furthermore, sports compression garments can differ considerably to medical compression garments with regard to interface pressure applied, graduated compression design and fabric type (elastic vs. inelastic). Despite an increasing proportion of studies reporting interface pressures in the sports compression literature, portable pressure measuring devices used to obtain pressure values lack comparison with a reference standard. Authors have attempted to assess the reliability of portable devices [1,2], however comparison with a medical device is absent in the literature. By assessing criterion validity and identifying an appropriate portable pressure monitor, this will assist with interpretation of applied pressures in a wider context and enable garment comparison with standardised pressure classifications (Chapter 3).

Evidence that compression garments positively influences exercise performance is limited [3], however physiological changes observed during locomotion are often observed. A recent meta-analysis reported small positive effects of compression clothing on running economy, biomechanical variables, blood lactate clearance and rating of perceived exertion [4], however garments included in this review vary by fabric composition, limb coverage and interface pressure. A lack of consistency in research methodologies has brought about a situation where much of the literature is unique in its own right. Comparison of outcomes between studies investigating two different types of compression garment (i.e. compression tights and below-knee stockings) should be conducted with caution in light of the varied body coverage and subsequent extent of interface pressure applied across a limb. Compression tights elicit external pressure across the full length of the leg (hip-to-ankle) and

therefore offer greater interaction with the knee and hip joint and upper and lower leg musculature compared with below-knee stockings. However, the majority of research investigating the physiological influence of compression clothing during running has utilised either compression socks or below-knee stockings [4]. Limited focus to date has been directed towards the role of full-length tights on the cardiovascular response during exercise (Chapter 4).

During long-distance endurance exercise, energy provision is primarily derived from aerobic metabolism. Three deterministic physiological variables are commonly associated with endurance running performance, including maximal oxygen uptake, lactate threshold/fractional utilisation of $\dot{V}O_{2max}$ and running economy [5–7]. Evidence suggests that during dynamic exercise in healthy individuals, compression clothing has no effect on maximal oxygen uptake or blood lactate concentration [8]. However, mixed results are reported regarding running economy [9,10]. Running economy reflects the metabolic cost of sustaining a particular running speed, representing the translation of energy turnover into linear running velocity [11]. Should compression tights produce an ergogenic effect on running economy, it is conceivable that this may contribute toward enhanced endurance running performance. Tightly controlled investigations are warranted to investigate the role of garment interface pressure and exercise intensity on measures of running economy with and without compression tights (Chapter 5).

Tissue muscle saturation is typically measured using near-infrared spectroscopy (NIRS). This non-invasive optical technique reveals *in vivo* muscle oxygenation and haemodynamic status and may provide a mechanistic explanation for the observed changes in running economy with compression tights. Wireless, portable NIRS devices offer the opportunity to monitor haemodynamic change in a dynamic field setting. However, as smaller and cheaper devices become commercially available, users must first be confident in the test-retest reliability and comparative performance of these measurement devices (Chapter 6).

Few studies have attempted to assess the role of compression tights on running economy at speeds reflecting an individual's long-distance competition pace. It is, after all, the exercise intensity most

important to the individual and the potential implications of wearing compression tights is of obvious interest to athletes, coaches and researchers. As running economy is a composite of mechanical and metabolic factors, assessment of substrate utilization, running kinematics and muscle oxygenation at competition pace is required. To maximise the likelihood of observing any effect, garments must apply a minimal pressure threshold [12] (Chapter 7).

A schematic of the thesis structure is provided in Figure 1-1.

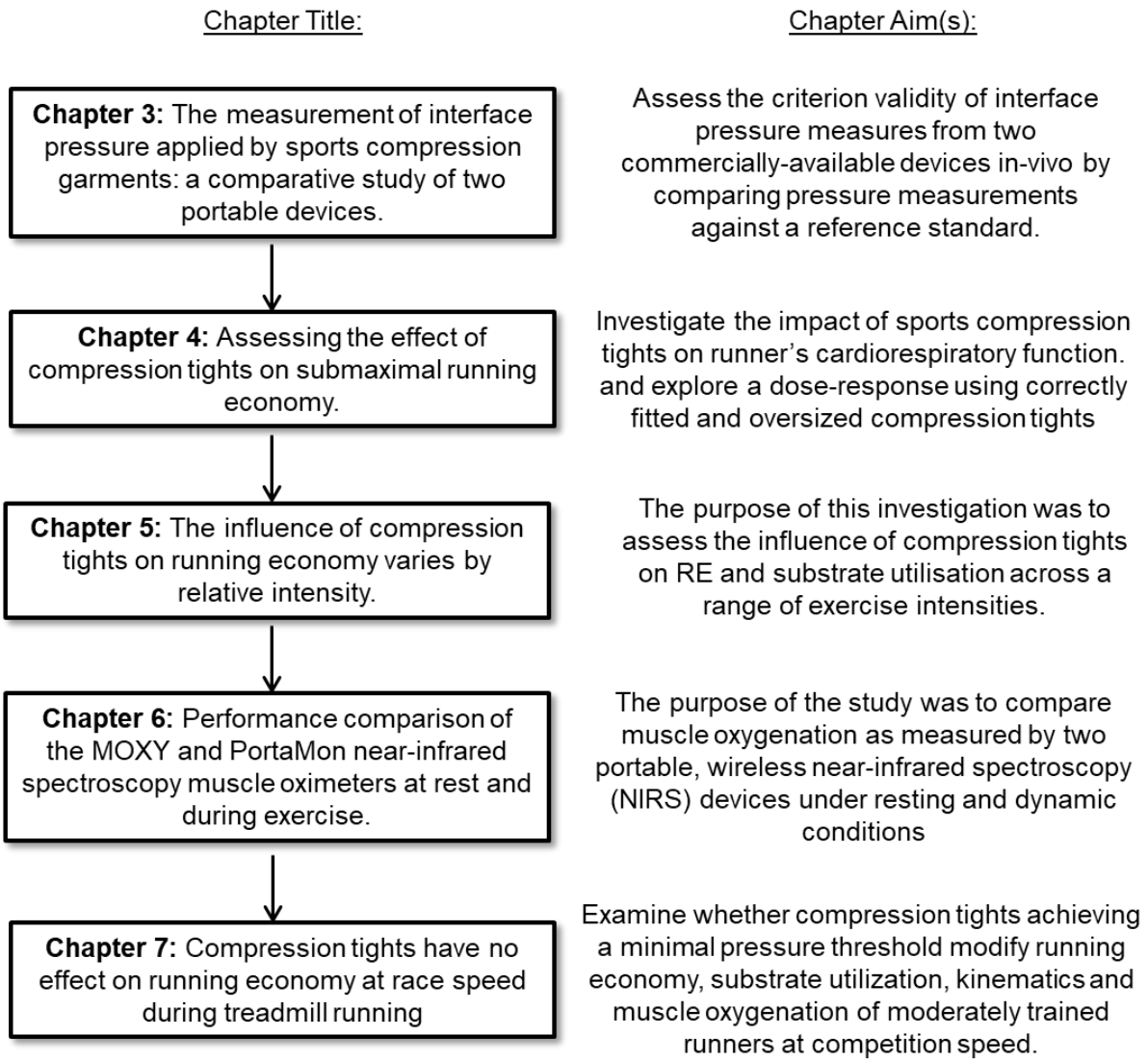


Figure 1-1 *An overview of thesis structure and chapter aims.*

2 Literature Review

This chapter provides a brief history and general introduction to the application of compression garments (CG). This is followed by a description of the current system used to classify medical CGs based on garment pressures. Then follows a critical discussion of sports compression studies, with special reference to the measurement of garment interface pressures and inconsistencies between methods of assessment.

The document next discusses performance studies investigating endurance and high intensity exercise outcomes when lower body CGs are worn. Physiological responses to exercise with compression will then be systematically discussed to critique the evidence for mechanisms thought to evoke a physiological response. The summary provided at the end of this chapter offers insight into potential future research directions based on current literature.

2.1 Historical context of lower body compression

The theory of applying local compression to human limbs was initially driven by clinical interest towards decreasing deep venous dilation and increasing blood flow velocity [13,14]. The clinical complications associated with aging include an increased prevalence of thromboembolic disease. As such, methods to minimise symptoms of phlebothrombosis and venous thrombosis were of particular interest. Early investigations supported the application of garments providing graduated compression in the management of diseases of venous deficiency including; leg ulcers [15], deep vein thrombosis [16,17] varicose veins [18,19] and venous thrombosis [20]. For further detail, Clark and Demers [21] provide an extensive historical review of the experimental evidence and therapeutic applications of lower body positive pressure.

All CGs apply mechanical pressure upon the body's surface; stabilizing and providing support to underlying tissues [3]. Mechanical pressure (termed 'interface pressure') is the product of the garment fabrics and their properties and the garment's anatomical fit. The fabric used in manufacturing

determines both ‘physical’ and ‘mechanical’ properties of the CG. Physical properties influence the CG ability to transfer heat and/or moisture vapour, while mechanical aspects, such as elastic modulus, elongation and relaxation time establish the extension and recovery behaviour [22]. CG are typically fitted dependent upon generic anthropometric measures including height, body mass and chest circumference, highlighting a particular problem when using generalized sizing systems. MacRae *et al.*, [3] highlights that individuals in the same dimensional range for a garment size i.e. size ‘large’, would likely vary in body morphology, thus vary in the applied pressure from the garment. To achieve the desired effect and/or treat a particular medical condition, the correct fit is of paramount importance. Undersized or oversized garments may provide levels of compression that are not ideal for a specific individual, whether that be too little compression to elicit a physiological influence, or too much compression that it inhibits limb movement, blood flow, feel uncomfortable or even cause tissue damage [23].

2.2 Medical compression: classifications

National standards for compression hosiery have been developed mainly as prerequisites for reimbursement. These guidelines set out requirements such as testing methods, yarn specification, compression gradient and durability [24]. There are few national standards for compression hosiery, i.e.

- British standard for graduated compression hosiery, anti-embolism hosiery and graduated support hosiery BS661210:2018 [25]
- German standard RAL-GZ for medical compression hosiery 387:1[26],
- French standard ASQUL [27].

Each of these standards are not consistent with one another, differing in recommended levels of pressure, classification of garments, method of pressure assessment and sizing guidelines. At present, there is no accepted International or European standard with regard to medical or sporting

compression classifications (mmHg). Attempts were made to produce a European standard (draft standard: ENV 12718:2001), but a consensus could not be achieved and the standard was cancelled in 2005 [28].

The US employs a different system of classification for CGs, however this is not unified within any specific 'standards' documentation (i.e. an FDA regulated classification). Most US compression hosiery manufacturers simply state the range of compression expected from their garments.

The recommendations set out by the regional standards differ between one another in relation to the amount of pressure exerted at the ankle and gradient of pressure up the leg. The British standard [25] lists three compression classifications and recommends graduated design based upon the nearest inferior anatomical landmark i.e. thigh compression as a percentage of calf compression (Table 2-1).

Table 2-1. Pressure and residual pressure ratio according to the BS 661210:2018 standard

		Residual pressure ratio (%)	
Compression class	Pressure at ankle (mmHg)	Proportion of ankle compression at calf	Proportion of calf compression at thigh
I	6 – 10	< 100	< 100
II	11 – 18	80 max	85 max
III	> 19	70 max	70 max

The German standard [26] classifies compression hosiery into four compression classes (Table 2-2). The standard also provides predefined pressure ratios (residual pressure ratio), defined as the pressure exerted by hosiery at a point of the leg above the ankle, expressed as a percentage based on the pressure at the ankle.

Table 2-2. Pressure and residual pressure ratio according to the RAL-standard

Compression class	Compression intensity	Pressure at ankle (mmHg)	Residual pressure ratio (%)		
			Upper ankle	Maximum calf	Mid -thigh
I	Low	18 – 21	70 -100	50 - 80	20 - 60
II	Moderate	23 – 32	70 -100	50 - 80	20 - 50
III	High	34 – 46	70 -100	50 - 70	20 - 40
IV	Very High	> 49	70 -100	50 - 70	20 - 40

The European standard (ENV 12718:2001) proposed five compression classifications, of which, these replicated the RAL standards closely (Table 1-3). However, this draft proposal also included a lower classification, incorporating compression hosiery with a pressure of 10 – 14 mmHg at the ankle (Class A).

Table 2-3. Pressure and residual pressure ratio according to the ENV 12718:2001 standard

Compression class	Compression intensity	Pressure at ankle (mmHg)	Residual pressure ratio (%)		
			Upper ankle	Maximum calf	Mid -thigh
A	Light	10 – 14	70 -100	50 - 80	20 - 60
I	Mild	15 - 21	70 -100	50 - 80	20 - 60
II	Moderate	23 – 32	70 -100	50 - 80	20 - 50
III	Strong	34 – 46	70 -100	50 -80	20 - 40
IV	Very Strong	> 49	70 -100	50 -80	20 - 40

2.3 Medical compression: measurement of pressure

Classification of the pressure exerted by CG on the lower limbs varies between countries. These variations likely impact decisions in clinical practice and possibly the design of research. Pressure is defined as a force per unit of surface area, for example Newton/m^2 or cN/cm^2 [29]. However, the

international measurement unit “millimetres of mercury” (mmHg) is favoured [30] and easily transformed from force/cm^2 to mmHg using the following conversion;

$$1\ N/cm^2 = 75.006\ mmHg$$

The pressure exerted by medical garments is established by dynamometers specific to the regional compression standard, i.e. French, British or German standards. These include the IFTH dynamometer (French standard; Fig. 2-1), the HATRA Mrk 2 (British standard; Fig. 2-2) hose pressure and the HOSY (German standard; Fig 2-3) measurement system.

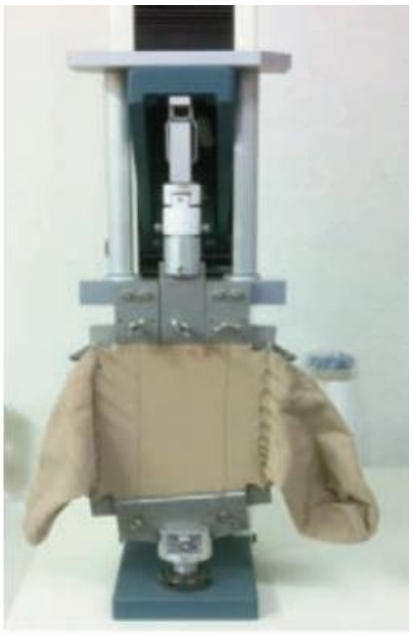


Figure 2-1. *Photograph of the IFTH dynamometer (image courtesy of Cornu-Thenard et al., [29]).*

Figure 2-2 *Photograph of the HATRA Mrk 2 dynamometer (image courtesy of Segar Technology).*

Figure 2-3 *Photograph of the HOSY measurement system.*

Each dynamometer measures fabric tension in the garment. Laplace's Law is then applied to calculate the pressure delivered to a cylinder of know radius that is covered with a fabric sleeve [31]:

$$P = T/R \qquad \text{(Eq. 1)}$$

Where P is the pressure (Pa), T is the tension (N) and R is the radius of the cylinder (m). However, the pressure of CGs is usually expressed as mmHg, fabric tension is measured per unit length and limb circumference is measured instead of limb radius; hence, units in equation (1) are usually converted to units common within the industry. Equation (2) is a result of unit conversions:

$$P = \frac{KT}{C} \qquad \text{(Eq. 2)}$$

Where *P* is the pressure (mmHg), *K* = 470, the conversion constant, *T* is the fabric tension (N/cm), and *C* is the cylinder circumference (cm). This equation relates the radial pressure exerted by the wall of a distended tube, the circumferential tension in the wall of the tube and its radius of curvature. The radius used assumes a circular cross section of the same girth, i.e. a cylinder (Fig 2-4).

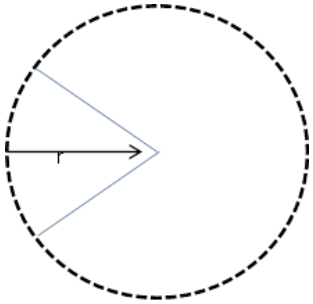


Figure 2-4 *Graphical illustration of a cylinder with circular cross section of the same girth. The fundamental principle of Laplace's Law.*

This assumption is a critical limitation of the larger medical compression devices, in that human limb morphology is not a perfect cylindrical shape, and even less so during dynamic movement, therefore the cross-sectional shape of the limb is in a constant flux. Pressures calculated using Laplace's Law provide an average pressure applied around the cylinder, however, in reality, these pressures vary at a given cross section of a human limb due to the different radius of curvature (Fig 2-5). The different radius of curvature around the same cross-section of a limb results in different pressures applied at various anatomical orientations. In Fig 2-5, the smaller radius of curvature will result in a higher level of pressure, therefore in this example, pressure applied at the anterior aspect of the limb is greater than that of the posterior.

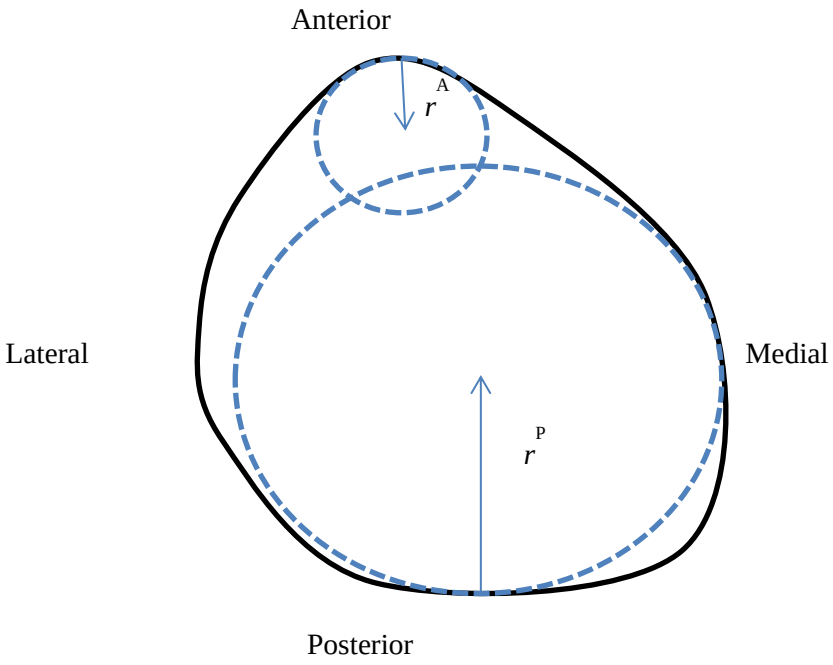


Figure 2-5 *Cross section of the lower leg. Illustration of differing radiuses of curvature at the anterior and posterior orientation of the lower leg.*

Furthermore, Macintyre *et al.,* [31] evaluated the Laplace's Law for pressure prediction using pressure measurements on a cylinder with different curvature radiuses. The authors demonstrated that the Laplace formula significantly overestimated the pressure exerted on small cylinders, however those with a greater circumference (>30 cm) were accurately predicted. This finding has implications in the theoretical modelling of medical garment pressures because the ankle pressure determines the remaining pressures applied upwards of the ankle (residual pressure ranges; see Table 2-1 – 2-3). It is expected that Laplace's formula will overestimate the ankle pressure due to the relatively low circumference (RAL [26] ankle circumference size guides range from 18 – 30 cm). As such, the limitations of using predictive formulae led researchers and practitioners to look for methods of assessing *in vivo* interface pressure. As a consequence, demand for smaller, more portable measuring devices has increased, whereby direct measurements at specific anatomical locations can be measured in individuals.

2.4 Portable pressure measuring devices

Various small, portable, pneumatic pressure transducers, connected to an air bladder via small tubing are available. These are thin, flexible, adjustable and optimised for different applications and different measuring regimes.

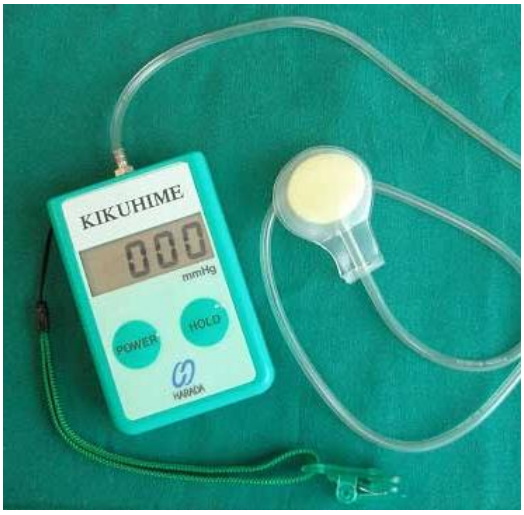
Prevalent pneumatic portable devices used to assess interface pressure in compression science include the PicoPress (Microlab, Padua, Italy; Fig 2-6), Kikuhime (Meditrade, Soro, Denmark; Fig 2-7) and the SiGaT Tester (Ganzoni-Sigvaris, St Gallen, Switzerland) devices. The portable devices work by placing a small circular bladder at a defined anatomical location (i.e. maximum calf girth). Once in place, a small amount of air is pushed up the tubing into the bladder using the in-built syringe. The screen on the device will display the applied pressure as mmHg. When pressure is measured *in vivo*, between garment and the surface of a limb, it is referred to as 'interface pressure'.

Partsch and Mosti [1] investigated the linearity, reliability and accuracy of the aforementioned portable pressure devices. Using the legs of human volunteers to assess the reliability, it was reported that the PicoPress produced the lowest average coefficient of variation (2.79%), followed by the Kikuhime (4.17%) and SiGaT (8.52%). Device accuracy was determined by comparing the reported pressure with the pressure applied via a sphygmomanometer cuff. At pressures <20mmHg, the PicoPress® reported the highest accuracy (<2 mmHg) and the Kikuhime the lowest (6 – 7 mmHg). The SiGaT device has also been found to report false-high pressure readings due to the large air bladder. When fully inflated, the bladder thickness stretches the garment and subsequently results in an artificial pressure increase [32]. Gaied *et al.*, [33] state that results obtained from *in vivo* devices are dependent upon the dimensions of the bladder, with larger bladders being more sensitive to variations in limb diameter. In light of these findings, recommendations for the measurement of interface pressure [34] suggest that the sensor/bladder should be thin and flexible, and smaller sensors used for mapping of a circumferential pressure pattern. Large sensor areas (over 5 cm^2) should be used for measuring the interface pressure of larger areas, thus taking advantage of the local pressure

distribution being averaged because of the changing curvature. Further, Ferguson-Pell *et al.*, [35] recommend that the maximal thickness of the sensor/bladders should be 0.5 mm.

	Size (unit indicated)
Bladder diameter	5 cm
Bladder thickness	< 0.3 mm

Figure 2-6 *The PicoPress compression device, showing the unit, pressure bladder and bladder dimensions (image courtesy of MediGroup Australia)*



	Size (unit indicated)
Bladder diameter	4 x 3 cm
Bladder thickness	> 5 mm

Figure 2-7 *The Kikuhime compression device, showing the unit and pressure bladder (image courtesy of* www.ebm-guidelines.com*)*

Debate is on-going regarding the strengths and weaknesses of either *in vitro* measures (i.e. HOSY / HATRA) and *in vivo* devices (i.e. portable pneumatic pressure transducers). Portable devices measure the dynamic interface pressure and report individual-specific compression values based upon a

person's unique limb morphology. However, there is no agreement which device is most accurate or the precise anatomical locations that require assessment.

The combination of different pressure devices and anatomical locations assessed, confounded with no agreed industry 'gold standard', gives rise to inherent risks when trying to compare outcomes of studies when these fundamental methodological aspects differ between studies.

2.5 Sports compression: measurement of interface pressure

Unlike medical CGs, the optimal interface pressure or compression gradient for athletic purposes is unknown. Some sports compression manufacturers have opted for unique garment designs i.e. static pressure gradient (same interface pressure throughout the limb) or negative compression gradient (increasing interface pressure from the ankle to calf). A bibliographic search began with the collection of papers from PubMed to explore the range of interface pressures and devices used for the in-vivo assessment of sports compression garments. The keywords *sports compression stockings, garments,* and *exercise* and the combination of them all were used in the search. Additional articles were obtained through cross-references with the initial search. The inclusion criteria were as follows: garment covers lower limb, interface pressure reported at ankle and calf location, in-vivo assessment performed by researchers. A total of 542 articles were identified by electronic search and 14 of these met the inclusion criteria (Figure 2-8). Table 2-4 provides a summary of sports compression studies (*n* = 14) reporting *in vivo* interface pressure applied at the ankle and calf. The studies listed in this table include those reporting interface pressures at the ankle and calf as a minimum and therefore give an indication of the pressure gradient. Of the 26 individual garments reported, 58% applied a positive compression gradient (higher interface pressure at the ankle) (n = 15) and the remaining 42% report a negative gradient. However, the influence of gradient design or interface pressure on sporting performance remains to be elucidated. Beliard *et al.,* [36] state that heterogeneity between studies may result in conflicting findings and mask any true efficacy of compression.

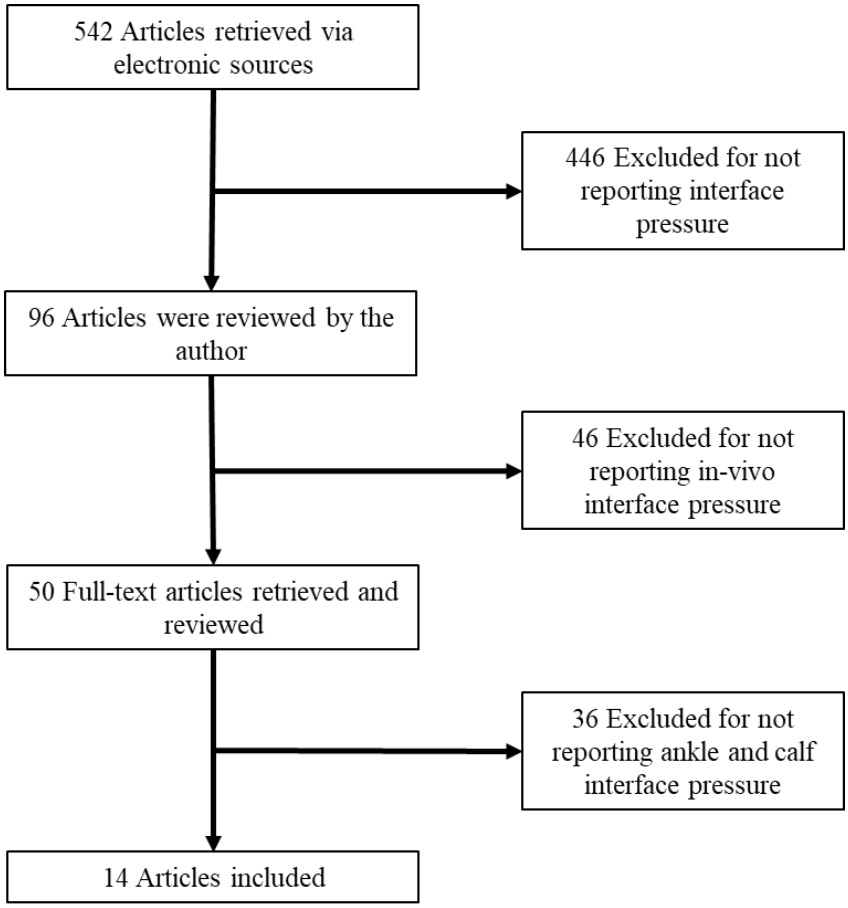


Figure 2-8 *Search strategy for the review of in-vivo interface pressure assessment.*

Furthermore, interface pressure is often unreported in studies using sports compression and when values are stated, the source or method is not always documented. This gives rise to uncertainty whether values where independently examined or manufacturers-reported pressures. Macrae *et* al., [37] identified 58 sports compression studies published over a five year period (2011 – 2015), with 74% reporting the interface pressure, however only 34% of authors measured the pressure.

Table 2-4 Published sports compression studies reporting *in vivo* interface pressure

Ref.	Study	Device	Orientation of measurement site	Garment manufacturer	Interface pressure (mmHg)	
					Ankle	Calf
[38]	Scanlan	Kikuhime	medial ankle + calf	SKINS	19.5	17.3
[39]	Ali (1)	Kikuhime	lateral ankle + calf	Julius Zorn	11	8
[39]	Ali (2)	Kikuhime	lateral ankle + calf	Julius Zorn	26	15
[40]	Sear	Kikuhime	medial ankle + calf	SKINS	17.8	15.1
[41]	Lovell	Kikuhime	-	Body Science	20	15
[42]	De Glanville	Kikuhime	-	SKINS	6	14.7
[43]	Hamlin	Kikuhime	-	SKINS	8.6	13.4
[44]	Reich-Schupke (1)	Kikuhime	-	CEP	17	28
[44]	Reich-Schupke (2)	Kikuhime	-	Falke	11	20
[44]	Reich-Schupke (3)	Kikuhime	-	Sigvaris	15	19
[44]	Reich-Schupke (4)	Kikuhime	-	X-Bionic	11	15
[44]	Reich-Schupke (5)	Kikuhime	-	2XU	17	28
[45]	Brophy-Williams (1)	Kikuhime	medial ankle + calf	-	9	20
[45]	Brophy-Williams (2)	Kikuhime	medial ankle + calf	-	15	25
[46]	Sperlich (1)	SIGaT	-	Sigvaris	21	13
[46]	Sperlich (2)	SIGaT	-	Sigvaris	31	23
[46]	Sperlich (3)	SIGaT	-	Sigvaris	39	32
[46]	Sperlich (4)	SIGaT	-	Sigvaris	46	39
[47]	Wahl (1)	SIGaT	-	-	21	13
[47]	Wahl (2)	SIGaT	-	-	31	23
[47]	Wahl (3)	SIGaT	-	-	46	39
[48]	Mosti (1)	PicoPress	medial ankle + calf	Pierre Fabre	25	22
[48]	Mosti (2)	PicoPress	medial ankle + calf	Pierre Fabre	20	31.5
[49]	Faulkner	PicoPress	achilles + medial calf	SKINS	6.2	13.2
[50]	Pruscino	Talley Medical	-	2XU	19.1	7.2
[51]	Maton	Salzman MKIII	medial ankle + calf	Innothera	17	14

2.6 Sports compression and exercise performance

Strategies that bring about measurable improvements in performance are highly sought after by athletes. Undoubtedly, athletic talent, comprehensive training programmes and optimal dietary intake all contribute towards athletic development and peak performance, however, factors such as clothing and technological advances, be it advances in electronic devices or fabric properties, are also deemed potential ergogenic aids, for which athletes are prepared to invest time and money into.

World records have been set by athletes donning CGs, reinforcing the link between compression clothing and elite performance [52], and whilst these world records are the result of talent and training, the decision for the athletes to wear these garments demonstrates the confidence held in the garments to aid performance.

The popularity of compression clothing within a range of sports, particularly endurance athletes, continues to increase, with monthly unit sales in the US increasing from 5,399 (value of $285,250 p/m) in January 2008, to 22,186 in November 2010 (value of $950,712 p/m) [53]. It was predicted that by 2019 the global market for compression apparel would grow at a compound annual growth rate of 5.1% and have reached $3.4 billion [54]. The increasing sales are a result of both high performance and recreational athletes wearing CG, in particular, at endurance events such as running and triathlon competitions [47].

2.6.1 Endurance exercise

Table 2-5 summarizes the research investigating the effects of compression on endurance running defined as activity lasting ≥10 min and measured as time trial performance, distance completed or time to exhaustion. Of 16 studies identified, five reported positive effects of CG on running performance [40,47,55–57], however evidence appears equivocal, with studies revealing no change in performance [47,52,58–65], or even a detrimental effect [66]. Previous meta-analyses have evaluated the influence of CG on performance [4,36,67–69]. Born *et al.*, [67] report a small improvement in performance when time to exhaustion and time-trial assessments are grouped together (effect size =

0.15). A subsequent meta-analysis was performed on time to exhaustion and time trial performance separately [4]. In this instance CG had little or no effect on time trial performance ranging from 400 m to marathon distance (mean $g = 0.03 \pm 0.15$), however time to exhaustion in incremental or step tests or runs to exhaustion revealed small positive effects (mean $g = 0.27 \pm 0.33$). Mota *et al.*, [68] conducted a review of compression stockings and reported a minor number of studies demonstrate an improved performance (3 out of 21). In contrast, the authors identified that wearing stockings during exercise could benefit muscle function or fatigue indicators immediately after and hours after an exercise bout. The conclusions of Mota *et al.*, [68] support those of Beliard *et al.*,[36] who found performance was unchanged regardless of the level of interface pressure. Interestingly, this was the first and only review that analysed the relationship between interface pressure and performance outcomes. However, it should be noted that the authors obtained similar garments to those used in the original investigations conducted 3 – 11 years previous. Clearly, this method assumes that garment design remained unchanged between the original investigation and the time in which the review took place. Da Silva *et al.*,[69] conducted a meta-analysis investigating the association of lower limb CG and high intensity exercise performance. Analysis of performance outcomes were grouped into three distance categories; 50 – 400 m, 800 – 3000 m and >5000 m. Of the four studies included in the >5000 m category, the authors report a weighted mean difference of 1.01 s (95% CI; -84.8 – 86.8), concluding that lower limb CGs are not associated with improved running performance.

The varied findings reported in the aforementioned reviews and meta-analyses may be explained by different methodological approaches and the grouping of exercise modality. For example, Engel *et al.*, [4] focused specifically on running performance whilst three other systematic reviews or meta-analyses combine running performance with other modalities (i.e. cycling) [36,67,68]. Furthermore, only Mota *et al.*, [68] focused on a specific garment type (stockings), whereas the remaining reviews include a combination of CG, possibly concealing a garment type effect. It would appear that some limitations of the literature (Chapter 2.8) are also relevant when comparing the findings of systematic reviews and meta-analyses. Despite the popularity of CGs among elite and recreational athletes, the evidence for enhanced endurance performance remains limited.

Table 2-5 Summary of literature investigating the influence of compression garments on endurance running performance

Author	N (Sex)	Garment	Interface Pressure (mmHg)			Exercise Modality and Protocol	Findings
			Ankle	Calf	Thigh		
Berry & McMurray [70]	6 (M)	Below-knee stockings	18	8	-	$\dot{V}O_{2max}$ test (2 min stages)	↔ No effect on time to exhaustion (P>0.05)
Ali *et al* [65]	14 (M)	Below-knee stockings	20	14	-	1) Multi-stage shuttle run 2) 10 km time trial run	↔ No effect on running distance (P>0.05) ↔ No effect on 10 km time trial (P>0.05)
Duffield & Portus [56]	10 (M)	Long tight and long sleeve top	NR	NR	NR	30 min repeated 20 m sprints and shuttles	↑ Small increase in total distance covered (*d* = 0.2-0.4)
Higgins *et al* [57]	9 (F)	Long tight	NR	NR	NR	4 x 15 min netball specific exercises	↔ No effect in total distance covered (P = 0.07) ↑ Large increase on distance covered at high speed (*d*=0.86)
Kemmler *et al* [55]	21 (M)	Below-knee stockings	24	20	-	Running $\dot{V}O_{2max}$ test (5 min stages)	↑ Increase in time to fatigue (P <0.05) ↑ Increase in total work completed (P <0.05)

Sperlich *et al* [8]	15 (M)	1) Below-knee stockings 2) Long tight 3) Long tight and long sleeve top	targeted at 20 mmHg			Running to volitional fatigue at fixed intensity	↔ No effect on time to exhaustion (P>0.05)
Sear *et al* [40]	8 (M)	Whole body garment	17.8	15.1	13.1	Prolonged high intensity intermittent exercise test (45 min)	↑ Medium increase in total distance covered (*d* = 0.6) and ↑ Medium increase in distance covered at low intensity (*d* = 0.6)
Menetrier *et al* [59]	14 (M)	Below-knee stockings	15	27	-	Running to volitional fatigue at fixed intensity (100% v$\dot{V}O_{2max}$)	↔ No effect on time to exhaustion (P>0.05)
Ali *et al* [52]	9 (M) 3 (F)	Below-knee stockings	15 21 32	12 18 23	- - -	10 km running time trial	↔ No effect on 10 km time trial (P>0.05)
Wahl *et al* [47]	9 (M)	Below-knee stockings	21	13	-	Running to volitional fatigue at fixed intensity (70% $\dot{V}O_{2max}$) (1% gradient increase every 1 min)	↑ Small increase in time to exhaustion (*d* = 0.2)
Barwood *et al* [60]	8 (M)	Long tights	NR	20	11	5 km time trial (in 32 °C)	↔ No effect on 5 km time trial (P>0.05)

Vercruyssen *et al* [61]	11 (M)	Below-knee stockings	18	18	-	15.6 km trail-running race	↔ No effect on 15.6 km trail-running performance (P>0.05)
Del Coso *et al* [62]	36 (NR)	Below-knee stockings	NR	NR	NR	Half ironman performance time	↔ No effect on half ironman performance (P>0.05)
Bieuzen *et al* [71]	11 (M)	Below-knee stockings	-	25	-	15.6 km trail race	↔ No effect on 15.6 km trail-running performance (P>0.05)
Rider *et al* [66]	7 (M) 3 (F)	Below-knee stockings	20 (*manufacturer claim*)	15	-	Running $\dot{V}O_{2max}$ test (5 min stages)	↓ Decrease in time to exhaustion (P<0.05)
Areces *et al* [64]	30 (M) 4 (F)	Below-knee stockings	20-25 (*manufacturer claim*)	-	-	Marathon performance time	↔ No effect on marathon performance (P>0.05)

NR= not reported; M= male; F= female. $\dot{V}O_{2max}$ = maximum volume of oxygen uptake; $v\dot{V}O_{2max}$ = velocity at maximum volume of oxygen uptake; P<0.05 = statistically significant, *d* = effect size. ↔ no change with CG, ↑ improvement with CG, ↓ worsening with CG.

2.6.2 High intensity running and sprint performance

Table 2-6 summarizes the research investigating the effects of compression on high intensity running and sprint performance. Studies within this search criterion include those of either single or repeated sprint efforts, assessing either time to completion, time to exhaustion at high intensity workloads or rate of fatigue over a repeated bout of maximal sprints. Of 14 studies identified, 11 reported no effect of CGs on high intensity running and sprint performance [8,10,49,56,72–79], however four studies revealed a positive effect [57,79–81], and one observing a detrimental effect [8].

Born *et al.*, [80] report a statistically significant improvement with compression clothing. The authors report improved 30 m sprint time during the final set of 10 sprints during a 30 x 30 sprint test when wearing long compression tights. However, this particular study was investigating a 'novel' garment design, with adhesive silicone strips placed within the garment, differentiating this particular garment with many of the previous studies assessing a 'traditional' CG. The authors also report a reduced hip flexion angle and increased stride length in their investigation of repeated sprint performance. This elegant investigation assessed a number of cardiorespiratory, metabolic, hemodynamic, perceptual, neuronal and biomechanical parameters, concluding that the improved repeated sprint performance is due to altered sprint mechanics.

Systematic reviews and meta-analyses provide a collective overview of the available literature. The combined analysis of five studies produced an overall small positive effect size (ES = 0.12) for improvements in single and repeated sprints of 10 – 60 m [67]. Furthermore, using weighted mean differences, Da Silva *et al.*, [69] revealed a 6.1 s (95% CI; -7.2 – 19.4) improvement in running performance between 800 – 3000 m. Although not statistically significant, the authors highlight the practical relevance, suggesting a 6 s improvement could greatly impact a race over such distances. At shorter race distances (50 – 400 m) the weighted mean difference was 0.06 s (95% CI; -2.0 – 2.1), revealing that the influence of CG might be intensity specific. The influence of CGs in relation to exercise intensity is explored further in Chapter 6.

Table 2-6 Summary of literature investigating the influence of compression garments on sprint running performance

Author	N (Sex)	Garment	Interface Pressure (mmHg)			Exercise Modality and Protocol	Findings
			Ankle	Calf	Thigh		
Doan *et al* [74]	10 (M)	Shorts	NR	NR	NR	60 m sprint time	↔ No effect on 60 m sprint (P>0.05)
Bernhardt & Anderson [75]	10 (M) 3 (F)	Shorts	NR	NR	NR	20 m sprint	↔ No effect on 20 m sprint time (P>0.05)
Duffield & Portus [56]	10 (M)	Whole body garment	NR	NR	NR	Intermittent repeated sprint exercise protocol (20 m sprint every minute for 30 min)	↔ No effect on repeated sprint performance (P>0.05)
Duffield *et al* [77]	10 (M)	Whole body garment	NR	NR	NR	5 x 20 m repeated sprint protocol following a simulated team game	↔ No effect on mean sprint time (P>0.05)
Higgins *et al* [57]	9 (F)	Long tight	NR	NR	NR	4 x 15 minute netball specific circuit including 20 m sprint at the end of each 15 min quarter	↑ Small decrease in 20 m sprint time (*d* = 0.23)
Houghton *et al* [78]	12 (M)	Knee length shorts and short sleeve top	NR	NR	NR	4 x 15 minute LIST including 15 m sprint at the end of each stage	↔ No effect on 15 m sprint time (P>0.05)

Sperlich *et al.*, [8]	15 (M)	1) Below-knee stockings	targeting 20			15 min treadmill run at 70% V̇O2max followed by time to exhaustion at peak running velocity	↓ Small decrease in time to exhaustion with stockings and whole body garments (*d* = 0.25 - 0.28)
		2) Long tights	targeting 20				↔ No effect on time to exhaustion with long tights (*d* = 0.13)
		3) Whole body garment	targeting 20				
Dascombe *et al* [10]	11 (M)	1) Correctly fitted tights	NR	19.2	13.7	Progressive maximal test followed by time to exhaustion at 90% V̇O2max	↔ No effect on time to exhaustion (P>0.05)
		2) Undersized long tights	NR	21.7	15.9		
Goh *et al*, [79]	10 (M)	Long tights	NR	13.6	8.6	Running to volitional fatigue at vVO2max (at 10° and 32 °C)	↑ Small increase in time to exhaustion at 32 °C (*d* = 0.48)
							↔ No effect on time to exhaustion at 10°C (*d* = 0.15)
Varela-Sanz *et al* [81]	13 (M) 3 (F)	Below-knee stockings	15 - 22	NR	-	Running to volitional fatigue at fixed intensity (105% of recent 10 km pace)	↑ Small increase in time to exhaustion (*d* = 0.32)
Faulkner *et al* [49]	11 (M)	1) Long tights	6.2	13.2	7.1	400 m sprint	↔ No effect on 400 m sprint time (P>0.05)
		2) Shorts + calf stockings	14.2	19.9	7.6		

Born *et al* [80]	12 (F)	Long tights	NR	21.7	17.5	30 x 30 m sprints (1 sprint per minute)	↑ Decrease in final 10 x 30 m sprint time ($P<0.05$)
Venckunas *et al* [72]	13 (F)	Below knee stockings	17	NR	18	400 m sprint following 30 minutes steady state (7:30 min/mile pace for 4km)	↔ No effect on 400 m sprint time ($P>0.05$)
Perez *et al* [73]	14 (M) 2 (F)	Below knee stockings	15-20	NR	-	1 km run at maximal speed	↔ No effect on 1 km maximal speed ($P>0.05$)

NR= not reported; M= male; F= female. $\dot{V}O_{2max}$ = maximum volume of oxygen uptake; $v\dot{V}O_{2max}$ = velocity at maximum volume of oxygen uptake; LIST = Loughborough intermittent shuttle test. $P<0.05$ = statistically significant, *d* = effect size. ↔ no change with CG, ↑ improvement with CG, ↓ worsening with CG.

2.7 Sports compression and physiological responses

Physiological responses to compression originate from mechanical pressure applied to the underlying tissue and the stabilizing support offered by the garment (Figure 2-9). External pressure applied by a CG increases peripheral tissue pressure [82], and subsequently redirects blood flow to the deep veins. The redirected blood and narrowing of veins increases blood flow velocity [13], and in turn, alters arterial [83] and venous [82] flow. Increased arterial flow will increase the delivery of oxygen-rich arterial blood to the working muscles [84], whilst increases in venous flow enables more rapid removal of waste metabolites [85]. In addition, by increasing venous flow, CGs can reduce exercise induced limb swelling [86].

Other physiological responses to CG include augmented mechanoreceptor activation, improved proprioception and altered running mechanics. Furthermore, the stabilizing effect of compression around a limb is thought to reduce muscle oscillation during exercise tasks that cause excessive limb vibration i.e. running [87]. Lower muscle oscillation is associated with reduced muscle fibre activation [88] and lower oxygen consumption during exercise [9].

Conversely, the potential risks or negative effects of compression application are not widely reported beyond those associated with excessive interface pressure. During standing, deep veins in the lower leg are narrowed by an external pressure of 42 mmHg and nearly occluded at 82 mmHg [89]. However, commercially available sports CGs do not typically exceed 30 mmHg and therefore the risks associated with prolonged occlusion are unlikely. Further psychological and physiological responses that may be counter-productive to the exercising individual include an increased perceived body temperature [72] and elevated skin temperature [78]. During exercise, heat loss is often a desirable, however if CGs attenuate the heat loss capacity this may lead to thermal discomfort, increased thermoregulatory strain and impaired exercise performance. Furthermore, residual sweat in the CG following exercise may lead to thermal discomfort due to unwanted heat loss (‘post-exercise chill’) and therefore CGs should have a short drying time [37]. The following chapter discusses many of the underlying mechanisms linked with sports compression in relation to exercise performance.

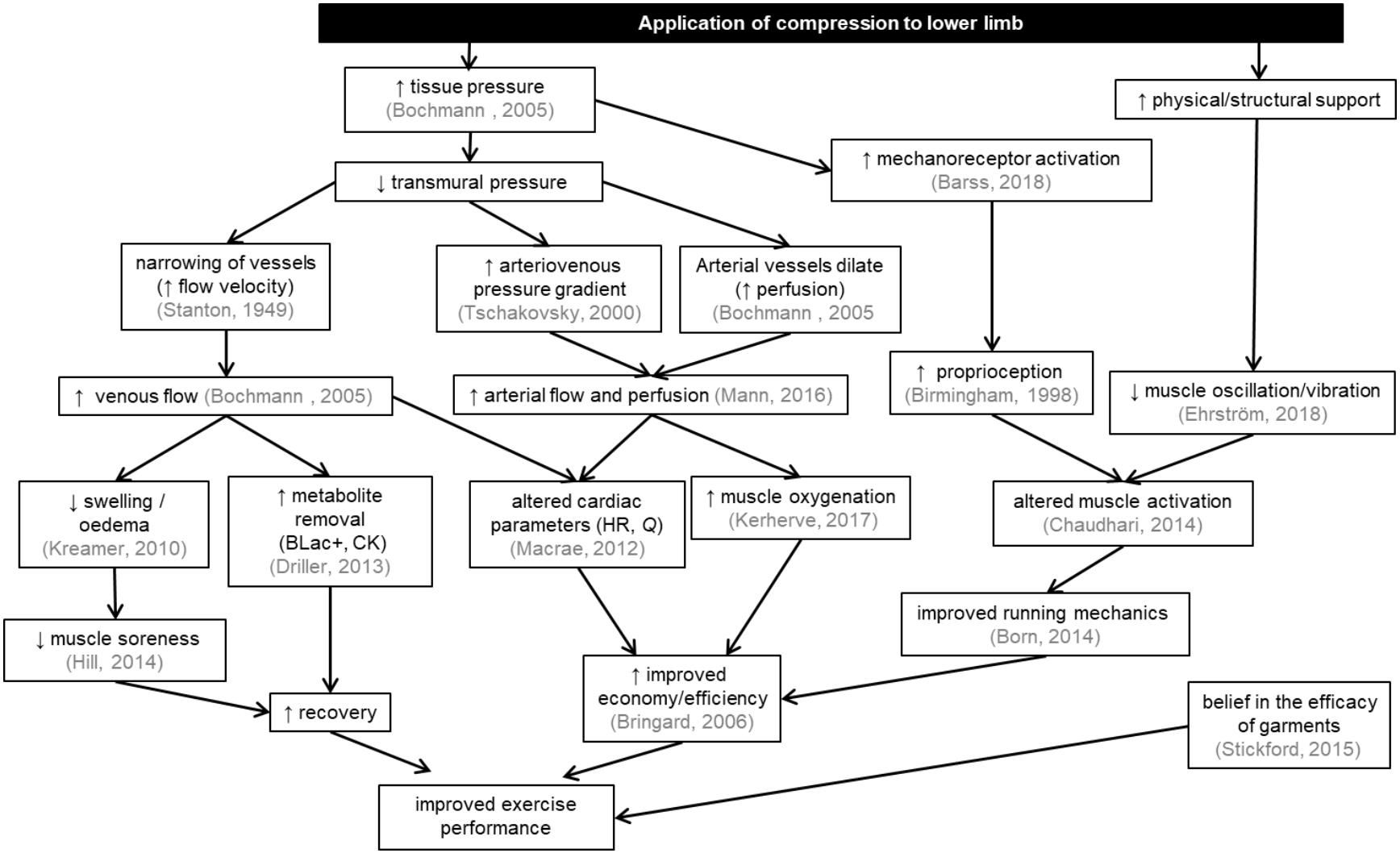


Figure 2-9 *A schematic representation of the mechanisms hypothesised in which compression clothing contributes toward athletic performance* [9,13,90–95,80,82–88].

2.7.1 Venous blood flow

The physiological impact of CGs in relation to cardiovascular response has been widely researched, with particular attention focused on venous blood flow velocity [82] and venous cross-sectional diameter [13]. The mechanism responsible for the increase in venous flow and decrease in venous stasis is via a reduction in the cross-sectional area of the vein [96]. Blood stasis is also shown to reduce under compression (23-24 mmHg), in both supine and standing participants [97]. This is of interest to athletes recovering from exercise induced muscle damage and hope to gain from a reduction in swelling and removal of waste metabolites. In a supine or recumbent position, compression produces an increase in venous flow velocity in healthy participants [98], however, in an upright position, changes in velocity are not reported. Furthermore, during exercise intensities reflective of training or competition, there is little evidence to suggest that compression influences venous return, cardiac output or stroke volume [3]. These findings indicate that even if changes in vein diameter and venous blood velocity are observed in healthy individuals, this does not inevitably indicate increases in flow volume per unit of time, and hence, improved venous return [3].

2.7.2 Arterial blood flow

External pressures of ~30 mmHg applied from the ankle to knee brought about an increase local arterial flow, increasing pulsatile blood flow by up to 45% when in the supine position [99]. Bochmann *et al.*, [82] demonstrated that arterial perfusion was increased by more than 200% in the forearm when a CG was worn, concluding that an applied pressure of ~20 mmHg resulted in the largest flow increase. Additional studies support the theory that an optimal pressure range may exist for blood flow augmentation, showing that pressures too high reduce blood flow and pressures too low do not affect flow.

The application of compression forces on a limb may increase muscle blood flow due to changes in arterial flow, rather than venous flow changes. Compression of underlying tissues reduces the transmural pressure gradient in local arterioles, thus causing vasodilation and increased blood flow to that area (the Bayliss effect) [100] . The reduction of transmural pressure and the myogenic response

(vessel relaxation) is the likely mediator for the observed increases in muscle flow and perfusion [82]. As previously alluded too, the improvement in arterial flow and consequently oxygen delivery may be of greater importance for an athlete compared with venous flow response under compression, or indeed alleviating venous stasis. Kemmler *et al.,* [55] stated that the application of a non-graduated, static compression stocking (similar interface pressure throughout the length of the garment) would bring about a greater benefit for an endurance athlete by way of enhanced arterial perfusion, and suggests that the need for graduated CGs within the athletic domain may be less of a concern. However, contrary to the speculation, arterial blood velocity under compression stockings remained unchanged during plantar-flexion exercise [101]. Future research should be targeted at step-wise increments of interface pressure whilst attempting to observe changes in haemodynamic response, ideally during a dynamic exercise modality. In light of the potential increase in muscle perfusion due to external pressure, a concurrent increase in muscle oxygen saturation would be expected.

2.7.3 Muscle oxygen saturation

Depending on body position and the interface pressure, compression clothing elicits a change in circulatory parameters such as venous and arterial flow. Furthermore, increased muscle oxygen saturation (measured using near infrared spectroscopy) has been observed in participants wearing compression [10,84,101]. Near-infrared spectroscopy (NIRS) is a non-invasive technique capable of providing valuable functional insights into skeletal muscle oxidative metabolism *in vivo* during exercise, in healthy and clinical populations [102]. The use of NIRS provides an appropriate measure of muscle oxygen consumption and blood volume measurement [103].

Bringard *et al.,* [97] reported an increase in calf muscle oxygenation as a result of compression tights in a supine and upright standing position (gastrocnemius pressure = 23 – 24 mmHg). Furthermore, the observed increase in calf muscle oxygenation is relative to the amount of interface pressure applied. Dermont *et al.,* [104] demonstrated increasing muscle oxygenation in a seated position as interface pressure increased from 16.5 mmHg to 36.5 mmHg. These findings suggest compression may increase muscle oxygen saturation at rest via its effects on haemodynamics.

However, compression induced changes in muscle oxygen saturation during and following exercise is less consistent. Vercruyssen *et al*., [61] investigated the influence of compression stockings (ankle-to-calf pressure 18-13 mmHg;) on prolonged trail running exercise. As part of this experiment, participants muscle oxygen saturation and muscle blood flow was assessed pre and post exercise (~5 min). The authors reported no difference between conditions (with and without compression stockings). However, the five minute delay between cessation of exercise and muscle oxygen saturation assessment limits insight into the acute effect of compression during the exercise bout. In agreement with Vercruyssen *et al*., [61], no change in muscle oxygen saturation following a 30 min submaximal run was observed [59]. However, noticeably higher oxygen saturation was observed with compression at rest (pre-exercise) and following a run to exhaustion at maximal aerobic speed. The interface pressure reported in these studies (18 – 27 mmHg) are the values provided by garment manufacturers and not measured directly.

Exercise reduces tissue oxygen; the rate at which oxygenation returns to normal is an index for rate of recovery. Increased oxygenation saturation recovery rate in the gastrocnemius medialis muscle was reported following two minutes of repeated heel raises [105]. It was identified that the relative slope of recovery rate is dependent upon the magnitude of interface pressure exerted, with an increasing oxygen saturation recovery rate as pressure increases. At interface pressures from 5-16 mmHg, there was a positive correlation in recovery rate; however without further data at increasing pressures, the 'optimal' interface pressure is unknown. It is expected that muscle oxygen saturation would stop increasing above a particular external pressure as peripheral and deep circulation will become impaired. Correctly fitted (as per garment manufacturers guideline) and undersized compression tights were compared with traditional running shorts during a time to exhaustion test (90% $v\dot{V}O_{2max}$) [10]. The undersized compression condition was implemented to provide varied compression levels and shed light on a possible interface pressure dose-response. During the time to exhaustion test, both compression conditions resulted in a significantly higher deoxyhaemoglobin (HHb) concentration when compared with the control. The authors suggest that the changes observed in peripheral muscle

circulation are due to increases in venous flow. Both compression conditions also reported a significantly lower HR during moderate intensity running (12 – 16 $km \cdot h^{-1}$), therefore this may be associated with the increased venous return and subsequent stroke volume via the Frank-Starling mechanism. Despite the circulatory changes observed in this investigation, no improvement in performance (time to exhaustion) or pulmonary oxygen uptake was reported. A possible explanation for the observed changes in peripheral circulation, particularly muscle oxygenation measures, may relate to the reduced heat-loss capacity when wearing CGs. Studies have reported an increased skin temperature of 0.5 - 2 °C under compression clothing [56,74,77,78], however this largely depends on the garment properties i.e. fabric composition. Thermoregulatory vasodilation may contribute towards an altered peripheral blood flow response [106], therefore changes in NIRS measures may be a result of elevated local and whole body temperatures [107].

2.7.4 Cardiovascular Function

If blood flow is augmented through the application of compression, a concomitant change to cardiac parameters would be expected. Indeed, compression stockings are reported to alter heart rate (HR), stroke volume and cardiac output in a standing position at rest [12]. However, during exercise, HR, stroke volume nor cardiac output appear affected by compression clothing at maximal [55,65] and submaximal intensities [9,38,39,46,56,77,78,101]. These findings suggest that any improvement to haemodynamic flow from external pressure probably reaches optimal function at rest, or at very low intensities [108]. It is likely that the exercise induced cardiac and blood flow response outweighs and severely diminishes any measurable benefit conferred by compression.

The donning of lower body compression clothing has no influence on measures of maximal [8,9,38,55,70] or submaximal [39,58] aerobic capacity. Despite this, the economy of O_2 consumption during exercise is shown to improve with compression when reported as per unit of distance (i.e. $ml O_2 \cdot kg^{-1} \cdot km^{-1}$). Bringard *et al.,* [9] reported a 9% reduction in the oxygen cost of running at 10, 12 and 14 $km \cdot h^{-1}$ when participants wore compression tights. The observed improvement in running economy (RE) was not apparent at a higher intensity (16 $km \cdot h^{-1}$),

More recently, authors have attempted to explore the influence of compression clothing on RE in more detail. Varela-Sanz *et al.,* [81] had participants undertake a steady state running protocol at a recent half-marathon pace (14.8 ± 2.2 km·h^{-1}) wearing either graduated compression stockings or traditional running shorts. Following this, a run to exhaustion at 105% of a recent best 10 km run time (17 ± 2 km·h^{-1}) was completed. RE was unchanged at half-marathon pace, however a large improvement (d = 0.90) was reported during the run to exhaustion. In addition, the relative heart rate experienced (%HR_{max}) during the run to exhaustion was significantly lower with compression stockings. The reduction in cardiac stress could infer that graduated compression stockings are more effective at an exercise intensity above that of half marathon pace (~82% $\dot{V}O_{2max}$) but below that of maximal aerobic speed (<100% $\dot{V}O_{2max}$).

Additional attempts to clarify the influence of CGs on exercise economy at various exercise intensities have demonstrated little benefit. The oxygen uptake during a run of 40 minutes at 80% of $\dot{V}O_{2max}$ did not differ between conditions when studying a group of well-trained athletes [39]. Stickford *et al.,* [94] assessed running economy and kinematics in highly trained male runners. Participants completed 4 min running bouts at 14, 16 and 18 km·h^{-1}. There were no significant differences in $\dot{V}O_2$ between clothing conditions, however, the average percentage change in submaximal $\dot{V}O_2$ with compression treatment ranged from -4.8% to + 5.1%. Running economy is strongly associated with running performance, such that a 5% improvement in RE may translate into a 3.8% improvement in distance running performance[109]. In light of this, the individual response to compression clothing should not be neglected.

Running economy is a multifactorial measure which reflects the sum of various cardiorespiratory, metabolic, biomechanical and neuromuscular characteristics [110]. If compression applied to the lower limb brings about a change to running economy, the mechanism(s) responsible may not necessarily be a result of haemodynamic change. Other measures that may shed light on the possible mechanisms explaining altered running economy include changes to muscle oscillation/vibration, running kinematics or proprioceptive ability.

2.7.5 Muscle oscillation

Long term exposure to vibrations that occur as a result of the heel strike during running can have detrimental effects on soft tissue. These include pain, loss of function [111] and reductions in muscle contractile force [112]. CGs may potentially attenuate soft tissue vibration during dynamic exercise such as running and jumping. CGs have been shown to reduce the movement of calf and thigh musculature during running [113] and counter-movement jumps [74]. A reduction in soft tissue vibration as a consequence of compression may subsequently alter the muscle activity. In support of this, CGs have been shown to reduce the cumulative shank muscle activity [114] and gastrocnemius activity [115] during submaximal running.

Compression-induced reductions in muscle activation, brought about by an attenuated soft tissue vibration, may have implications for running economy. It follows that if muscle force output can be maintained in the presence of lower levels of muscle fibre recruitment, oxygen cost may be reduced. However, despite significantly lower levels of soft tissue vibration and muscle activation with compression tights, running economy remained unchanged at speeds of 8 – 12 $km \cdot h^{-1}$ [113]. A possible explanation for the discordant effect of compression on running economy in this instance may be due to the duration of submaximal running (3 min). Steady-state $\dot{V}O_2$ is typically achieved after three minutes of exercise at a constant running speed [116], therefore the duration may have been too short to observe any measureable change to oxygen cost.

2.7.6 Proprioception

CGs are shown to activate both cutaneous and muscle mechanoreceptors at rest and during movement [90]. The altered excitability in the central nervous system may explain the observed improvements in joint position sense [91,117,118], one-leg balance (with eyes closed) [119] and reaching accuracy [90]. The application of external pressure is shown to assist as a 'filter function' of nonspecific mechanoreceptor activity, enhancing precision and movement sensitivity around the joint where compression is applied [90]. With heightened proprioceptive potential, it raises the notion that CGs may enhance kinaesthetic sense during dynamic sporting movement. Only two studies have

investigated the role of CGs on task precision during an athletic performance. Wearing an upper body CG was shown to improve fastball accuracy in collegiate baseball pitchers and improve driving, approach-shot and chipping accuracy in high-level collegiate golfers [120]. However, in contrast, throwing accuracy of cricketers is unchanged with full body (long tight and long sleeve top) compression clothing [56].

It is a plausible that pressure induced mechanoreceptor activation may lead to improved joint sense position in dynamic exercise, such as running. By improving joint sensing ability, an individual may favourably alter technique or gait. The following section will discuss the influence of CGs on running kinematics.

2.7.7 Running kinematics

CGs covering the hip region (tights and shorts) are shown to decrease active hip-joint range of motion at rest [75] and during counter-movement jumps [74], suggesting a potential 'ergogenic interplay' between compression and biomechanical factors [94]. However, during a time to exhaustion test at ~17 $km \cdot h^{-1}$, no differences were reported in running technique kinematics such as contact time and flight time with compression stockings [81]. Similarly, compression stockings produced no effect on gait variables at running speeds between 14 – 18 $km \cdot h^{-1}$ [94]. In contrast, changes to aerial time and leg stiffness were observed at 12 $km \cdot h^{-1}$ during a moderately flat 24 km trail run. In the same study, lower ground contact time, higher leg stiffness and higher vertical stiffness were also reported during an all-out hilly 24 km trail run [84]. Despite these findings, exercise performance did not improve.

The aforementioned studies all included below-knee compression stockings as the intervention condition. In light of the potential hip-joint range of motion interaction with CGs covering the hip, investigating the influence of compression tights or shorts on running kinematics is of interest. Stride length is reportedly reduced at running speeds of 10 and 14 $km \cdot h^{-1}$, but not above or below these speeds (8 or 18 $km \cdot h^{-1}$). Furthermore, modification to stride length was only observed in compression tights applying a high external pressure (calf = 33 mmHg; thigh = 20 mmHg). No change in stride

length was observed with compression tights applying a lower level of external pressure (calf = 23 mmHg; thigh = 11 mmHg).

Interestingly, it is suggested that athletes could require an accommodation period for systematically experiencing their benefit [81]. In support of the postulated accommodation period, reduced landing force during a fatiguing run was later reported following a period of 3 weeks training wearing graduated compression stockings (ankle = 24 mmHg; calf = 21 mmHg) [121].

2.8 Limitations to literature

Despite the number of publications, the sports compression category is relatively new, and many questions remain unanswered. A lack of consistency in research methodologies has brought about a situation where much of the literature is unique in its own right and therefore unable to compare outcomes between studies. This is apparent within all areas of compression related scientific evidence, however particularly exaggerated in the sports literature. The literature often fails to detail the type of garment worn, garment fabric properties, external pressure exerted, the duration in which the garments are worn, and the application of a placebo or control condition. Furthermore, various methodological approaches have resulted in different exercise intensities, types and duration [3]. It is conceivable to consider that the heterogeneity between studies may mask any true efficacy of compression, possibly only apparent with more restrictive experimental conditions implemented in future research [36].

Hill *et al*., [92] identify a number of additional limitations with sports compression literature including; small sample sizes, lack of placebo and a poorly described method used to randomise participants. Additionally, the garments used also vary widely and include upper body and lower body garments from a range of manufacturers, which are likely to exert different degrees of pressure.

Male and female runners exhibit different hip and knee mechanics during running [122]. Despite this sexual dimorphism, females are significantly underrepresented in sports and exercise medicine research [123] and more specifically within sports compression and running research. Engel *et al.,* [4]

included a total of 494 participants in a review of compression clothing and running performance. However, only 11% of these were female, highlighting the gender bias present in this domain of research. Therefore, care should be taken to account for gender when studying groups of male and female recreational runners (Chapter 7).

2.9 Summary

Research investigating the effectiveness of CGs during exercise is of particular interest to athletic populations. However, there are several facets of sports compression research that are yet to be explored in sufficient detail. The accurate assessment of garment interface pressure is of pressing importance. Many studies merely document the manufacturers reported pressures, therefore providing little insight into any potential pressure-response relationship. With the development of portable pressure monitors, it is possible that future sports compression research will tackle this issue. However, given the variety of portable pressure devices, it is critical that pressure monitors are assessed for consistency between devices and compared with reference-standard medical devices.

Meta-analyses report small increases in time to exhaustion [4], and practically relevant improvements over specific running distances (i.e. 800 – 3000 m) [69]. These small improvements, when observed, are challenging to delineate due to the confounding study methodologies implemented in the sports compression literature. Various garment types, different interface pressures applied by CG and the disparity in exercise modality, intensity and duration are a few examples of the challenges faced when evaluating the literature. However, of interest is the relationship between CG induced improvements in running economy and the associated impact this may have on performance [4,9,81,94]. Engel *et al.*, [4] indicate a potential small benefit (g = 0.21 ± 0.11) of CG on running economy. However the garment type ranged from calf sleeves, socks, long tights and whole body compression in the four studies included in the analysis. By pooling various garment types to produce a mean estimate illustrates once more the heterogeneity within the sports compression literature. Despite this, if the application of external pressure has the capability to meaningfully alter cardiovascular, biomechanical

or neuromuscular systems, these may have an interactive effect upon the energy cost of locomotion and subsequently improve running economy. While the findings are inconsistent, the application of compression to the hip, thigh, knee, calf and ankle has on occasion, demonstrated an adaptive response. Given that compression tights cover the full length of the leg, including the hip and knee joint, the use of these garments may provide the greatest opportunity to influence physiological parameters during submaximal running.

2.10 Thesis aim and objectives

This critical review of the literature has highlighted scope for further investigations that may enhance the understanding of CGs in the athletic domain. The aim of this thesis was to provide a comprehensive analysis of sports compression tights on the running economy of moderately trained runners. Prior to doing so, identification of an appropriate pressure measuring device provides confidence in the validity of interface pressures reported throughout the thesis. Subsequently, the interaction between compression tights, running economy and mechanisms underlying any potential physiological benefit is explored. This was addressed through the following objectives;

Objective 1) To identify a valid portable pressure device and the optimal *in vivo* anatomical orientation for interface pressure assessment. (Chapter 3)

Objective 2) To examine the effect of compression tights on running economy using garments of varying interface pressure. (Chapter 4)

Objective 3) To assess the influence of compression tights on running economy and substrate utilisation across a range of exercise intensities. (Chapter 5)

Objective 4) To compare two portable, wireless near-infrared spectroscopy devices under a variety of resting and dynamic conditions. (Chapter 6)

Objective 5) To test the efficacy of compression on running economy, substrate utilization, kinematics and muscle oxygenation. (Chapter 7)

3 The measurement of interface pressure applied by sports compression garments: a comparative study of two portable devices

3.1 Rationale

Reporting the interface pressure applied by sports CGs is becoming increasingly common. This offers the opportunity to compare study findings and explore the relationship between interface pressure and physiological response. However, to achieve this, devices used in the assessment of interface pressure must be reproducible and valid. Two portable pressure devices, popular in the sports compression literature and also commercially accessible, were selected and compared with a medical reference standard. Previous research has investigated the test-retest reliability of these devices *in vivo*, however no study has compared the values obtained *in vivo* with those calculated using a medical reference standard. Calibration with a medical standard offers the opportunity to identify a portable pressure monitor appropriate for future studies.

3.2 Abstract

The interface pressure applied by compression clothing is an important measure in evaluating the efficacy of the bio-physical impact of compression. The aim was to compare two portable pneumatic pressure measuring devices (PicoPress and Kikuhime), against a non-portable, Hohenstein System (HOSY) reference standard, used by medical regulatory agencies. Interface pressure obtained *in vivo* (calf) by the PicoPress and Kikuhime, were compared with HOSY. The mean bias and limits of agreement indicate the PicoPress satisfies the *a priori* thresholds for acceptable validity at the posterior and lateral orientation with calf stockings (-0.4[-3.3;2.5]; 0.5[-3.4;4.4] mmHg) and tights (0.2[-4.7;5.1]; 1.2[-0.3;5.4] mmHg) respectively. The Kikuhime did not satisfy thresholds for acceptable validity at any orientation, overestimating the pressure compared with HOSY. We recommend using the PicoPress, specifically at the posterior or lateral aspect of the calf. This is of

particular relevance when the garment is applying relatively low levels of pressure, applicable to sports compression.

3.3 Introduction

CGs are popular clothing choices among recreational and professional athletes during and after exercise. These garments have been shown to enhance athletic performance and accelerate recovery following strenuous exercise [4,92].

Despite the prospective benefits, little is known regarding the optimal 'interface-pressure' a CG should apply to a particular limb, to produce the greatest athletic benefit [2]. In contrast, the application of pressure to the lower extremities via tight fitting, elastic garments, is extensively researched in the clinical field and is part of standard care in patients with chronic venous insufficiency and lymphatic disease [124]. Unlike sports CGs, medical compression stockings undergo a standardised assessment procedure to quantify the pressure applied; therefore recommendations can be made in relation to the treatment protocol including a desired interface pressure [125]. Such recommendations cannot be made with regard to athletic performance or recovery due to a number of methodological limitations. Heterogeneity of published literature relating to research design is commonplace, including but not limited to; variation in garment design, duration of wear, type of garment and limb coverage. Furthermore, authors fail to measure the pressure of garments [59] or values are provided by the garment manufacturer and are not directly measured [126]. If garment pressure is reported, the measurement devices used by researchers vary greatly, ranging from portable units and force-transducers to medical-grade devices. Until the measurement of the interface pressure elicited by sports CGs is standardised, developing a consensus and furthering the field regarding dose-response will continue to be a challenge. The reporting of pressure, obtained directly by research scientists and clinicians would progress the field of sports compression and

enable the investigation of optimal interface pressures (dosage) and gradients required for improved performance and recovery outcomes [2].

A critical aspect of effective compression therapy is that the appropriate level of pressure is applied to the limb. Portable pressure sensing devices offer quick, low cost, *in vivo* assessment during dynamic movement. Validation of measures made *in vivo* by these devices is necessary to establish preferable devices and inform best practice.

Current guidelines for the assessment of *in vivo* interface pressure list 22 portable devices [34], including pneumatic, piezoelectric, resistive and capacitive sensors. The authors state that the quantification of interface pressure will enable comparisons between clinical trials to assess dosage and the correlation with clinical and physiological measurements. However, many of the portable devices listed in the guidelines have not been validated nor compared with alternative methods of pressure assessment i.e. fixed, non-portable reference devices.

Portable devices must undergo rigorous assessment to identify if variation exists between units. Furthermore, the accuracy of these devices versus a clinically relevant reference standard is necessary to provide a comparative assessment of performance. By identifying portable devices with acceptable accuracy, guidelines can be developed further and ultimately assist with understanding the bio-physical impact of interface pressure on physiological response and performance outcomes.

In light of this, we assessed the criterion validity of interface pressure measures from two commercially available devices *in vivo* by comparing pressure measurements against a reference standard.

3.4 Methods

We compared two portable devices (Kikuhime and PicoPress) commonly used with a ‘reference standard’ system (HOSY). The HOSY is a mandatory testing system for interface pressure

compliance, required for the classification and certification of medical compression hosiery. Two warp knitted compression garments were used, including calf- stockings (Figure 3-1a), covering the ankle to below the knee (Skins™ Men's Compression MX Calf Stockings, Riverwood, Australia) and full-length tights (Figure 3-1b), covering the body from ankle to waist (Skins™ Men's Compression A400 Long Tights, Riverwood, Australia).

Figure 3-1 *Image of Skins™ Men's Compression (a) MX Calf Stockings and (b) A400 Long Tights (images courtesy of www.skinscompression.com).*

The fabric properties of the two CGs were investigated for performance including fabric weight using Sartorius balance. Fabric thickness was measured using a Shirley thickness gauge (Mitutoyo, Japan) [127]. Fabric count (number of wales and courses) was measured with a simple eye piece lens that had 5x magnification. Stretch and recovery was also evaluated to determine the stretch characteristics of fabric in length and cross wise direction using Fryma Extensiometer [128] and 3 kg load was applied (Table 3-1). All fabrics were conditioned in standard laboratory conditions (20 ± 2°C, 65 ±

0% relative humidity) for 24 h prior to the fabric tests [129]. Garments did not undergo pre-treatment washing prior to or between measurements.

Table 3-1 Fabric characteristics of the compression garments.

	Weight (g/m^2)	Thickness (mm)	Composition	Count (wpc x cpc)	Extension (%)	Residual extension(%)
Stockings	298 (2.83)	0.69 (0.00)	65% Nylon 35% elastane	420 x 250		
Length wise					52.67 (0.94)	2.67 (0.00)
Cross wise					96.67 (4.71)	2.00 (0.94)
Tights	199.33 (0.57)	0.57 (0.01)	76% Nylon 24% elastane	520 x 500		
Length wise					164.89 (13.87)	8.0 (3.52)
Cross wise					94.67 (2.67)	2.67 (1.33)

Number in the brackets indicates standard deviation; cpc – courses per mm; wpc – wales per mm

3.5 Reference Standard Device

The Hohenstein System (HOSY, Bönnigheim, Germany) is used to measure interface pressure and determine if garments meet the German 'medical compression hosiery' standards RAL GZ 387/1 [26]. The HOSY measures interface pressure (maximum resolution of 0.01 kPa), wear stretch (elongation %), tensile force (N/cm) and residual pressure (%). The device (Figure 3-3) comprises twenty individual tensile testing 'rods', each with a width of 50 mm. The force measurement takes place at the fixed clamp rod via short-distance electronic transducers. The measurement principle of the HOSY is based on the force exerted by compression fabric in circumferential direction, when stretched in a longitudinal direction to a specified length and subsequently in a transverse direction according to its size. For further details of the HOSY see the RAL GZ 387/1 standards [26].

3.5.1 Calibration

Pressure was measured on both garments at the location that corresponded with the maximum calf girth. The maximum calf girth, commonly referred to as 'location C' (Figure 3-2) in published guidelines [34] and standards [26], was chosen as interface pressures exerted in this region are commonly cited in both medical [130] and sports compression literature [10]. Prior to the measurement process, the ankle location (also referred to as 'location B') was manually identified on both garments and subsequently location C is marked at a height of 200 mm above this point. Calibration of the HOSY device takes place annually by attaching a 5 kg weight to each of the 20 tensioning clamps.

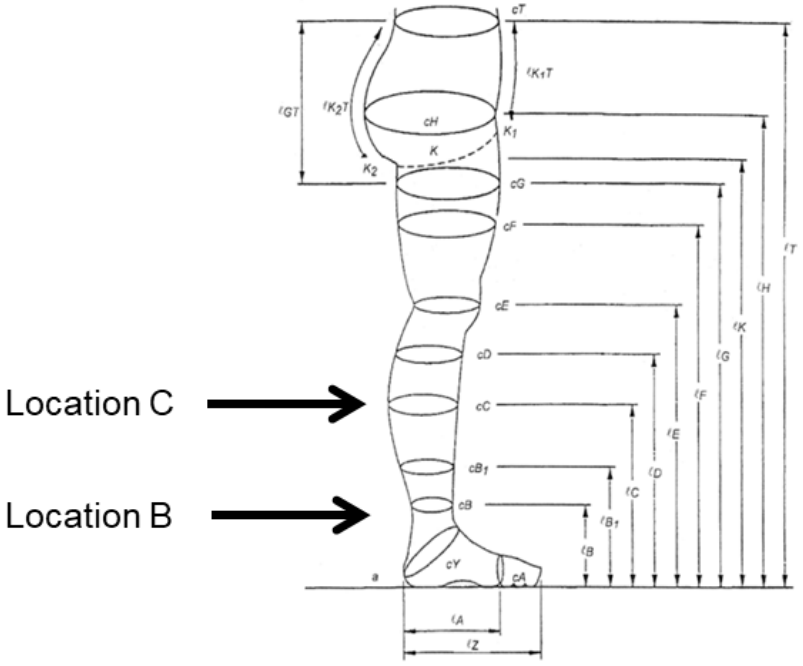


Figure 3-2 *Measuring point for the ankle (Location B) and maximum calf girth (Location C) (image courtesy of RAL GZ 387/1 [26]).*

3.6 Reference Standard Protocol

A qualified technician attached the garments and operated the HOSY device in a controlled laboratory environment (18 ± 0°C, 65 ± 0% relative humidity). Briefly, two clamps held the bottom of the garment in place (Figure 3-3a) with the remaining garment placed in each fixed clamp rod (Figure 3-3b). Once correctly fastened into the HOSY, the distance of location C (Figure 3-3c) from the bottom clamps was entered into the operating computer. The garment was stretched (loaded) and relaxed (unloaded) six times in the cross-wise direction. Each loading cycle extended the garment to the leg circumference. During the final loading phase the tensile force at each clamp was measured. The computer program calculates how far each tensioning clamp moves to achieve the desired circumference and the resultant elongation of the garment so that all clamps reach this position simultaneously after 20 seconds [26]. A minimum and maximum leg circumference of 370 and 400 mm at Location C was used for this investigation. Initially, the test-retest reliability of the HOSY was determined by measuring the tights twice. Between each assessment, the garment was unclamped and removed from the HOSY and reapplied by a qualified technician. The technical error of measurement (TEM) and coefficient of variation (CV) reported for the HOSY was 0.5 mmHg and 5.8% respectively. For all data analysis referring to the tights, the mean of the two repeated measures at minimum and maximum elongation was used. Calf stockings were measured on one occasion only.

Compression classification standards vary by country [131,132] but a unified classification of mild (10-19 mmHg) and moderate (20-29 mmHg) compression is proposed. With this in mind, when comparing portable devices with the reference standard and determining device validity, *a priori* thresholds are required. The criteria for acceptable validity was defined as a systematic bias of ±2 mmHg and a limit of agreement ±5 mmHg (of the mean bias). A bias of ±2 mmHg accounts for technical error of the HOSY and the resolution of the portable devices. Limits of agreement of ±5 mmHg identify the variability of the device vs. the reference standard accounting for the 10 mmHg classification range.

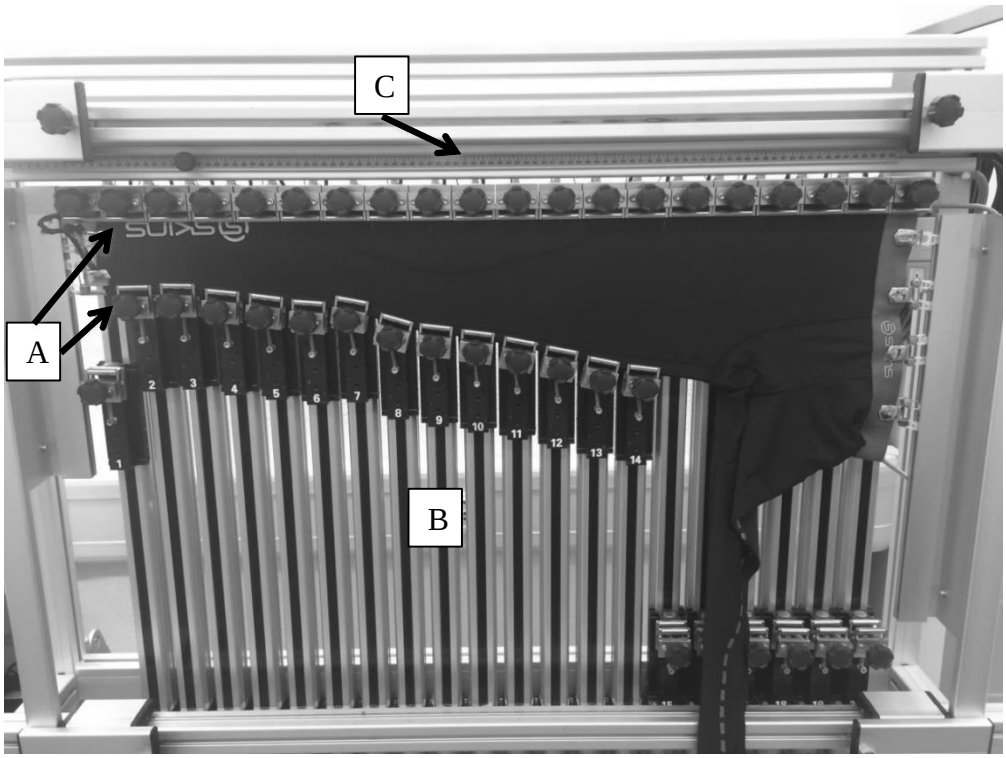


Figure 3-3 *The Hohenstein System (HOSY) showing (a) clamps holding the bottom of the garment, (b) 20 measuring rods with clamps and (c) measurement tape.*

3.7 Portable Devices

The PicoPress (Microlab, Padua, Italy) is a battery-operated device and comprises a 50 mm circular sensor manufactured from 200 μm thick flexible plastic tubing attached to the base unit. The Kikuhime (Meditrade, Soro, Denmark) comprises 30 x 38 mm oval sensor made from 3 mm polyurethane foam and connected to a transducer via silicone tubing. Both the PicoPress and Kikuhime operate through pressure being applied to the sensor, thereby displacing the air and acting on the pressure transducer housed in the battery-operated units. The PicoPress can measure pressure up to 189 mmHg; and the Kikuhime up to 120 mmHg both with a resolution of 1 mmHg.

3.7.1 Calibration

We calibrated devices according to the manufacturers' instructions. A self-calibration procedure is performed when switching the PicoPress unit on. Digital prompts on the device outline the calibration

procedure by inserting 2 ml of air into the sensor, setting the unit to read 0 mmHg when hanging freely. In the same position, the Kikuhime requires the user to manually zero the potentiometer. In light of the Kikuhime calibration method and unit resolution, there is an inherent calibration offset error of up to ± 0.49 mmHg [133].

3.8 Portable Device Protocols

3.8.1 Water-column method

To certify measurement validity and linearity from air-filled portable pressure systems such as the PicoPress and Kikuhime devices, the water column method provides a quick and in-expensive method making use of hydrostatic pressure.

As previously described [2], by placing the pressure sensor flat at the bottom of a water column, and filling the column with a specific volume of fluid, a known pressure will be placed on the sensor. Water depths were calculated to determine incremental pressures of 5 mmHg, from 5 to 25 mmHg, whereby the depth measurement was taken from the lowest point of the meniscus and the middle of the sensor. The depth of water (mm) to achieve the target pressures was calculated using the following equation,

$$a \text{ mmHg} = b \text{ mmH}_2\text{O} \times [7.356 \times 10^{-2}]$$

Five repeated measures were undertaken for each depth, which required the removal of water from the column each time, before returning it to achieve the predetermined depth.

3.8.2 *In vivo* protocol

Twelve recreationally active males (mean ± SD: age 19.1 ± 1.0 y, body mass 74.6 ± 4.8 kg, stature 1.77 ± 0.05 m) gave written informed consent to participate in the study in accordance with Declaration of Helsinki. The ethical committee at the University of Essex approved the current investigation.

All testing was performed in a controlled laboratory environment (18 ± 0°C, 50 ± 2% relative humidity). Upon arrival, the circumference of the participants calf was measured (location C = 380 ± 12 mm). All participants possessed a maximum calf girth between 370 and 400 mm. To ensure that garment Location C was accurately positioned at the correct limb height in-situ, position-markers on each garment were aligned with anatomical markings at the maximal calf-girth. The anterior, posterior, medial and lateral aspect were identified with a segmometer (Cescorf, Porto Alegre, Brazil). Limb width was measured at each orientation and the mid-point marked as the location for the portable device sensor. Using the PicoPress and Kikuhime devices, interface pressure at the anterior, posterior, medial and lateral aspect around the maximum calf girth was measured. The investigator placed the air-filled sensor of each device between the garment and skin, ensuring that the sensor remained flat. Participants stood upright with feet shoulder width apart during all measurements. Garment order was determined using a balanced two-Latin square design to minimize device and orientation order effect. For each anatomical site, three repeated measures were obtained at 30-second intervals.

3.8.3 Portable Devices Data Treatment

In vivo interface pressures were measured at four anatomical orientations and a fifth value calculated as the average of all four measures (i.e. lateral + medial + anterior + posterior / 4 = mean of four orientations ($\overline{x}$)). A Pearson's Product Moment correlation was used to analyse the linearity of the PicoPress and Kikuhime against the water column reference values. Data analyses were conducted using Graphpad Prism 7 (Graphpad Software, San Diego, California) and reported as mean ± standard deviation (SD) unless otherwise stated.

3.9 Data Analysis Agreement

Prior to comparing *in vivo* portable devices with a reference standard, interface pressures must be established for each participant for the reference device. The HOSY does not measure pressure

directly applied to the individual, instead, pressures are determined by elongating the garment to a pre-determined length, simulating the circumference of a limb. A simple linear regression was calculated to predict interface pressure based on the HOSY pressure values at minimum and maximum elongation. As the theoretical circumference increased by 10 mm, interface pressure applied by the stockings increased by 0.86 mmHg between 370 and 400 mm (19.3 – 21.9 mmHg; $y = 0.87x - 12.77$). The interface pressure of the tights increased 0.62 mmHg for every 10 mm increase in circumference (12.5 – 14.4 mmHg; $y = 0.62x - 10.32$). The regression equation was then used to determine individualized pressure from the reference standard by factoring the individuals' calf circumference. Calculation of the estimated HOSY interface pressure for each participant produced a mean [95% CI] pressure of 20.1 mmHg [19.5, 20.8] and 13.1 mmHg [12.6, 13.6] for the stockings and tights respectively. Having established reference values, comparisons can now be made with the portable, *in vivo* devices. Normalcy was assessed using the Kolmogorov-Smirnov test. The difference between the individualised HOSY values and portable device pressures were assessed for significance using a one-sample t-test (target value = 0). The method proposed by Bland and Altman [134] was used to assess agreement between the HOSY and each portable device at all anatomical orientations The difference between devices was calculated as the interface pressure (mmHg) of the HOSY minus the portable device (PicoPress or Kikuhime), providing bias values and upper and lower limits (± 1.96 SD). Difference was plotted as a function of the HOSY reference value [135] and linear regression used to calculate slope (*B*) of the HOSY versus portable device interface pressure. Analyses were performed using the Statistical Package for the Social Sciences (SPSS) version 25 (SPSS Inc., Chicago, Illinois) and the level of significance was set at $\alpha = 0.05$.

3.10 Results

The PicoPress and Kikuhime interface pressures produced a positive correlation when compared with the criterion water pressure. Correlation coefficients calculated to evaluate the linear association between the pressure applied by the water column and two portable pressure devices are shown in Figure 3-4.

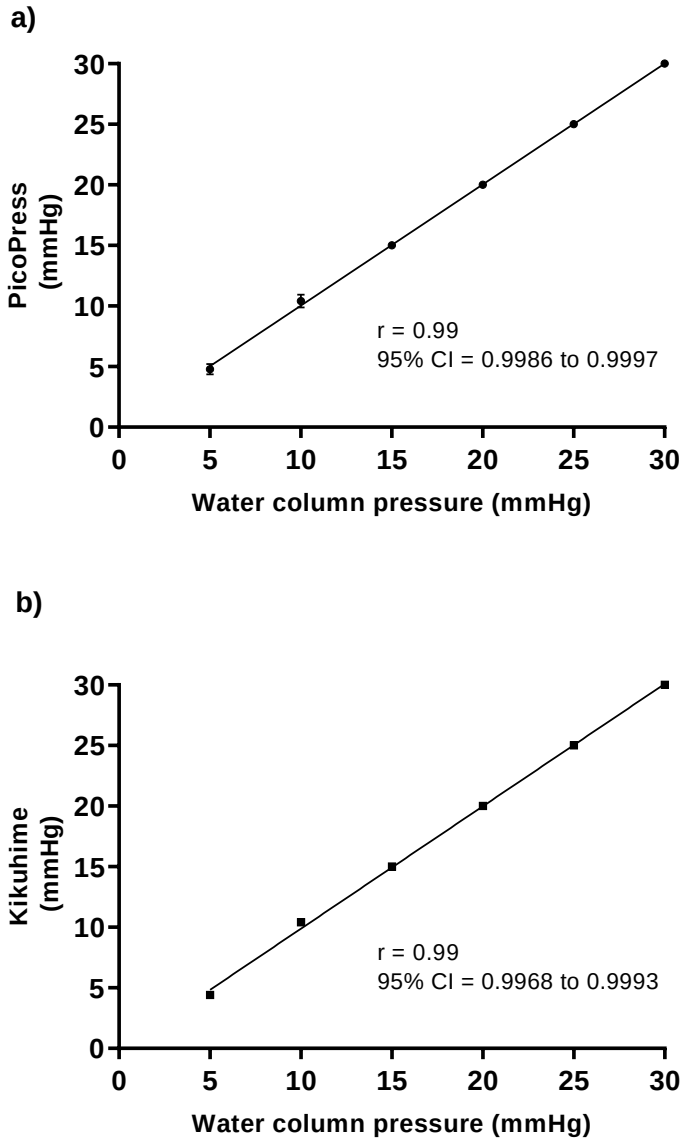


Figure 3-4 *Linearity and correlation coefficients for the (a) PicoPress and (b) Kikuhime device.*

The interface pressures obtained by the reference standard, PicoPress and Kikuhime for the stockings and tights are shown in Table 3-2 and 3-3 respectively.

The PicoPress produced values which agreed with the reference standard when measured at the posterior (-0.4 [-3.3; 2.5] mmHg) and lateral (0.5 [-3.4; 4.4] mmHg) orientations (Table 3-2). The positive mean bias values for measures at the anterior and medial orientation show PicoPress produced systematically higher values when compared with the reference standard, Table 3-2 shows

the Kikuhime produced values that were significantly higher (P<0.01) compared with the reference standard at all measurement orientations, with a bias ranging from -6.1 - -17.6 mmHg.

Table 3-3 shows the between-device agreement for tights. When compared with the reference standard, the PicoPress (Table 3-3) produced significantly higher values at the anterior orientation (P<0.01), but not at the posterior, medial and lateral orientation. Of the orientations, the posterior, lateral and mean satisfied the *a priori* thresholds for acceptable validity, reporting a bias of 0.2 [-4.7; 5.1], 1.2 [-0.3;5.4] and -0.6 [-4.5; 3.4] mmHg respectively. The Kikuhime produced interface pressure values that were higher than the HOSY. Regardless of orientation the Kikuhime had a mean bias >2 mmHg at all orientations other than the medial aspect. At the medial orientation, the mean bias was 2.0 mmHg but the limits of agreement were unacceptably wide and did not satisfy the validity threshold.

Of all the measurements obtained using both portable devices, the unstandardized slope coefficient produced values ranging from -.02 – 2.4. With the exception of the posterior orientation using the Kikuhime with calf stockings, all remaining slopes were positive. At the posterior and lateral orientation, the PicoPress satisfied the validity thresholds with both garments, demonstrating a small bias, acceptable limits of agreement and a negligible slope. This means the PicoPress, at two specific orientations, is an accurate proxy measure for interface pressure when compared with the reference standard.

Table 3-2 Interface pressure, significance, agreement values (bias and limits) and slope between HOSY and portable devices with stockings

	Interface Pressure (mmHg [SD])	P-value	Bias [95% LoA]	*B* [95% CI]
Orientation	PicoPress			
Anterior	29.3 [3.9]	<0.01	-9.2 [-1.8; -0.6]	2.4 [0.0 – 4.8]
Posterior	20.6 [1.5]	0.35	-0.4 [-3.3; 2.5]	0.5 [-0.4 – 1.4]
Medial	22.0 [2.1]	0.02	-1.8 [-6.5; 2.8]	1.1 [-0.3 – 2.5]
Lateral	19.6 [2.1]	0.37	0.5 [-3.4; 4.4]	0.4 [-0.9 – 1.7]
$\bar{x}$	22.9 [1.5]	<0.01	-2.7 [-6.4; 0.9]	1.1 [0.1 – 2.0]
	Kikuhime			
Anterior	37.7 [4.4]	<0.01	-17.6 [-26.8; -8.3]	1.7 [-1.2 – 4.6]
Posterior	26.2 [3.0]	<0.01	-6.1 [-11.4; -0.8]	-0.2 [-1.9 –1.6]
Medial	27.0 [3.8]	<0.01	-6.9 [-15.0; 1.2]	1.5 [-1.0 – 4.0]
Lateral	26.5 [3.8]	<0.01	-6.3 [-14.3; 1.6]	1.3 [-1.2 – 3.8
$\bar{x}$	29.4 [2.5]	<0.01	-9.2 [-14.6; -3.9]	1.1 [-0.5 – 2.7]

$\bar{x}$ = mean of four orientations; SD = standard deviation; LoA = limits of agreement; *B* = unstandardized beta coefficient of regression slope; CI = confidence interval. Mean [95% CI] HOSY pressure = 20.1 [19.5, 20.8] mmHg.

Table 3-3 Interface pressure, significance, agreement values (bias and limits) and slope between the HOSY and portable devices with tights

	Interface Pressure (mmHg [SD])	P-value	Bias [95% LoA]	*B* [95% CI]
Orientation	PicoPress			
Anterior	16.9 [2.9]	<0.01*	-3.8 [-10.1; 2.5]	2.0 [-0.6 - 4.7]
Posterior	12.9 [2.3]	0.82	0.2 [-4.7; 5.1]	1.3 [-0.9 – 3.4]
Medial	13.0 [2.7]	0.93	0.1 [-5.8; 6.0]	2.2 [-0.2 – 4.6]
Lateral	11.9 [1.9]	0.07	1.2 [-3.0; 5.4]	1.3 [-0.5 – 3.1]
$\bar{x}$	13.7 [1.6]	0.35	-0.6 [-4.5; 3.4]	1.7 [0.3 – 3.1]
	Kikuhime			
Anterior	21.0 [4.4]	<0.01*	-7.9 [-16.7; 1.0]	1.2 [-2.9 – 5.3]
Posterior	15.9 [2.2]	<0.01*	-2.9 [-7.0; 1.3]	0.2 [-1.8 – 2.2]
Medial	15.1 [3.4]	0.69	-2.0 [-8.6; 4.7]	0.6 [-2.5 – 3.8]
Lateral	15.1 [2.6]	0.03*	-2.1 [-7.4; 3.3]	1.2 [-1.2 – 3.6]
$\bar{x}$	16.8 [2.1]	<0.01*	-3.7 [-8.1; 0.7]	0.8 [-1.2 – 2.8]

$\bar{x}$ = mean of four orientations; SD = standard deviation; LoA = limits of agreement; *B* = unstandardized beta coefficient of regression slope; CI = confidence interval. Mean [95% CI] HOSY pressure = 13.1 [12.6, 13.6] mmHg.

3.11 Discussion

We investigated the validity of two portable pressure measurement devices. First, pressure values reported by two portable devices were compared with hydrostatic pressure using a water column method. Second, the two portable pressure devices were compared against reference standard values analogous to those used to determine the classifications of medical compression hosiery. In agreement with previous studies using the water column method [2,136,137] we confirmed the Kikuhime and PicoPress devices produced reliable *in vitro* measures of hydrostatic pressure (Figure 3-4). However, this method in isolation does not ensure validity *in vivo* as measurement error is the sum of instrumental error and the geometry / mechanical properties of the interface surface. The water column method is undertaken with the sensor in a flat position, whereas *in vivo* measures are commonly taken at locations where the surface is curved, potentially impacting upon the pressure

sensor performance [133]. At best, this technique offers the user a simple tool to assess unit precision and identify if inherent malfunctions with the pressure device exist. However, the water column method should not be used in isolation to determine the performance of a portable pressure monitor and its comparability with alternative garment pressure sensing devices.

The present *in vivo* assessment confirmed the extent to which the point pressures vary at different orientations. The results are comparable to that previously reported, in that interface pressure at the anterior orientation of the lower leg is greatest [138–140]. This is likely due to variation in the anatomic structure and shape of individual human legs. According to Laplace's law, the pressure exerted by a CG is inversely proportional to the radius of curvature at a given location. It follows that pressure applied at the tibialis anterior muscle will result in the highest circumferential pressure due to a smaller radius of curvature, when compared with the larger radius of the gastrocnemius (medial, lateral and posterior location).

The PicoPress showed acceptable agreement for posterior and lateral measures of interface pressure made in both garments. This prominent finding regarding device performance and location of assessment is important to advance the standardisation of compression testing. In contrast, the Kikuhime overestimated interface pressures in both garments and at all anatomical sites. Under a sphygmomanometer cuff at 20 mmHg, the Kikuhime has previously reported a pressure ~25 mmHg [141]. The Kikuhime systemic overestimation of interface pressure may misclassify compression garments. However, at 30 – 50 mmHg both devices reported accurate and matching values [141]. The validity of devices at lower pressures is important when assessing sports CGs which typically produce interface pressures of ~10 – 30 mmHg [36,142]. Differences in the size and shape of the air-filled sensors used in both devices might explain the observed bias. The PicoPress uses a circular sensor 40 mm in diameter whereas the Kikuhime uses smaller (38 x 30 mm) oval sensors with a smaller area (895 mm^2). When placed on a cylindrical shape, a smaller sensor will result in a reduced radius of curvature, possibly explaining the higher interface pressures reported by the Kikuhime.

The Kikuhime sensor is also 2 mm deeper than the PicoPress when inflated and also includes a foam insert. The increased depth of the Kikuhime creates a local protuberance when used *in vivo*. Any additional protrusion will distend the fabric of tight fitting garments causing an increase in tension and the sensor bulge will reduce the radius of curvature and result in a further increase in observed interface pressure [143].

The *B* slope coefficient is a product of the calculated HOSY values and compared with the interface pressure obtained with a portable device. The PicoPress values at the posterior and lateral orientation for both garments report a low, positive *B* slope (<1.5 mmHg). The positive slopes indicate that at the lower end of the reference standard interface pressure, the portable devices report a higher value, whereas at the higher end of the reference standard pressure, the portable devices tend to underestimate interface pressures.

3.11.1 Limitations

The current results are a product of the garment and device interaction whereby the specific garment fabrics have shown to play a pivotal role in altering the interface pressure. The garments used in the present study, whilst commercially available, do not reflect the wide range of fabric compositions used for sport and medical compression and therefore caution should be used to extrapolate the present findings across alternative fabrics.

3.11.2 Future Research

Future research should compare the interface pressure reported by portable pressure devices with CGs of a known pressure (i.e. 10, 20 and 30 mmHg). By using the PicoPress at the approved orientations, it will provide insight into the variability of pressure when off-the-shelf garments are measured.

3.11.3 Practical Implications

The PicoPress and Kikuhime are commonly cited devices in medical literature [144,145], sub-bandage pressure assessment [146,147], and as reference devices in the development of piezoresistive sensors [148]. However, in the current study, and in agreement with previous research [1,133,141],

significant discrepancies between the devices are evident. However, this study not only reports differences between portable devices, but also compares performance with a reference standard. This study contributes towards international standardization by identifying a portable pressure sensor (PicoPress) and assessment location (posterior and lateral) capable of replicating pressure values established from a reference standard. This is an important finding given the low-cost and speed in which garment pressure can be determined using a portable pressure monitor when compared with indirect methods. These findings are particularly relevant for researchers, garment designers and clinicians monitoring garment pressure, when interpreting the pressure applied in a wider context and comparing with the standardised pressure classifications.

3.12 Conclusion

Two portable pressure devices were rigorously assessed in order to contribute much needed future standardization of pressure evaluations for sports compression. When compared with a reference standard, the PicoPress provides a valid measure of interface pressure at the posterior and lateral location of the calf. From a practical, *in vivo* standpoint, we recommend using the PicoPress to assess interface pressure, specifically at the posterior or lateral aspect of the calf. This is of particular relevance when the garment is applying relatively low levels of pressure, applicable to sports compression.

4 Assessing the effect of compression tights on submaximal running economy.

4.1 Rationale

This study intended to explore the influence of compression tights on cardiorespiratory function. Having identified a portable pressure monitor with criterion validity when compared with a medical reference standard (Chapter 3), the PicoPress was used to assess garment interface pressure. In this study, correctly fitted and oversized compression tights where worn by recreationally active male runners and compared with running shorts. Assessment of cardiovascular parameters during submaximal exercise with two garment size variants provides an insight into a potential dose-response regarding interface pressure.

4.2 Abstract

Compression tights are the most commonly used sports compression wear, worn by recreational athletes globally. Despite their popularity, the influence of commercially available, low-pressure compression tights on cardiorespiratory function remains limited. This study investigated the effects of correctly sized and oversized compression tights applying a low interface pressure, on cardiorespiratory function, compared with a control garment. Eleven recreationally active participants completed a 15 min run at 60% peak aerobic running speed ($v\dot{V}O_{2max}$) on three occasions. Running economy (RE), respiratory exchange ratio, minute ventilation, breathing frequency, heart rate, and rating of perceived exertion were measured during the steady state run, with blood lactate collected post exercise. A small, *likely beneficial* improvement (95%:5%:0%; $\eta^2 = 0.55$) in RE at 60% $v\dot{V}O_{2max}$ was observed in the correctly sized compression condition when compared with control. All remaining variables reported unclear, trivial or possible differences between garment conditions. The findings suggest that wearing non-graduated, low pressure CGs have a likely benefit for submaximal RE, however it appears necessary that a certain level of interface pressure is required.

4.3 Introduction

CGs are an popular clothing choice among physically active individuals. As the demand for these specialised CGs grows in popularity with professional and recreationally active markets, the benefits cited by commercial companies are continually questioned [149]. Medical garments apply compression in a graduated fashion, with the greatest pressure applied at the distal location, reducing in pressure proximally. This garment design, when worn by patients with chronic venous insufficiency or healthy individuals at rest, increases blood flow velocity, reduces swelling and minimises venous stasis [150,151][150,151]. If enhanced calf skeletal-muscle pump function, improved venous return and lymphatic drainage are physiological responses to the application of compression clothing, it is understandable that sportspeople hope for an ergogenic benefit.

Compression tights, that cover the wearer from the waist to ankle, are the most commonly purchased sports compression wear, accounting for more than one-third of compression wear market revenue in 2015 [152]. However, there is a scarcity of literature assessing compression tights with recreationally active runners, despite being the largest consumer group. Of the studies that have specifically investigated the influence of compression tights on running performance, a reduced energy cost of running, by way of a decrease in oxygen uptake (VO_2) slow component [9] has been reported along with lower muscle activation in key running-related muscles during distance running [153]. Conversely, a detrimental effect of compression tights on running economy at low speeds is reported [10], suggesting that this may be a result of additional VO_2 required to overcome the resistance to movement that may be caused by compression tights. Other authors have reported no change in parameters such as time to exhaustion, heart rate [154], rating of perceived exertion [9], oxygen uptake or lactate during submaximal running [8] when compression tights are worn.

The inconsistency in sports compression literature is confounded by varied research methodologies, small participant numbers and the type of CG used (interface pressure exerted (mmHg), surface area covered and fabric properties). With reference to the interface pressure applied by CGs, standard

classifications exist for graduated medical compression hosiery [26]. However, there are no agreed interface pressure classifications for sports compression garments, nor an agreed approach as to how interface pressure should be measured. Broadly, medical classifications report 'low' pressure as 18-21 mmHg applied at the ankle and decreasing progressively up the leg [26]. However, sports CGs are reported to elicit an interface pressure below this minimum threshold [142], indicating that sports garments produce lower interface pressures than medical garments.

The primary aim of the present study was to investigate the impact of sports compression tights on recreational runner's cardiorespiratory function. Our secondary aim was to investigate a possible dose-response comparing running economy when wearing correctly fitted compression tights versus oversized garments. It was hypothesised that measures of cardiorespiratory function during running would be improved with correctly fitted compression, but not oversized garments.

4.4 Methods

Eleven healthy, non-smoking, recreationally active (>3 sport specific training sessions per week) males (mean ± SD; age 28.7 ± 6.6 years, weight 68.2 ± 5.3 kg, $\dot{V}O_{2max}$ 54.2 ± 4.9 $ml \cdot kg^{-1} \cdot min^{-1}$, $v\dot{V}O_{2max:}$ 19.2 ± 1.4 km h^{-1} (corrected for 1% gradient)) participated in the study. Participants kept a 3-day food and activity diary prior to preliminary testing. They were requested to follow the same dietary intake the day prior and day of testing for all subsequent testing dates. Participants were asked to refrain from exercise, caffeine and alcohol intake 24 hours prior to testing and refrain from strenuous exercise 48 hours prior. Furthermore, participants did not consume any food or fluid (excluding water) in the 2 hours prior to testing. Ethical approval was received from the University of Essex ethical committee. Participants provided written informed consent in accordance with the Declaration of Helsinki.

The compression tights used in this investigation, shown in Figure 4-1, were Skins ™ Men's Compression A400 Long Tights (Riverwood, Australia), and the correctly fitted garment for each participant was in accordance with the manufacturer's instructions. For the oversized garment

condition, participants wore two sizes above the manufacturer's instructions. The garments were made from warp knitted fabrics, with the fibre reported as 76% nylon and 24% elastane. Participants were blinded to the garment condition by removing the size label. The pressure exerted by the compression tights on the lower limbs were evaluated by the PicoPress® (Microlabs, Italy) pressure monitor which has a coefficient of variation of <5% at 20 mmHg,[1] and shown to satisfy criterion validity with a reference standard device (Chapter 3). Pressure measures were recorded at 3 anatomical locations (ankle = 5 cm above superior sphyrion, posterior calf = maximal calf girth and anterior thigh = mid-point between mid-trochanterion-tibiale laterale). The control garment consisted of loose fitting running shorts, thereby providing a comparison between compression tights and garments typically worn by recreational runners. Participants wore the same short-sleeved top and running shoes on all occasions.

Figure 4-1 *(a) Lateral and (b) anterior view of Skins ™ Men's Compression A400 Long Tights used in this investigation.*

The experimental protocol consisted of four sessions, held between 2-4 days apart for all participants. Each participant attended their sessions at the same time of day, with similar environmental conditions (temperature: 18 ± 1.0° C) to minimise variation in physiological parameters that might change with circadian rhythm. A crossover design was incorporated into the study; with garment order counterbalanced using a Latin square design.

The initial session determined individual maximal aerobic capacity ($\dot{V}O_{2max}$), and peak running speed during an incremental treadmill test ($v\dot{V}O_{2max}$). After a 5 min warm-up at 7 $km \cdot h^{-1}$ (0% gradient) participants completed an incremental exercise test on a treadmill (Saturn, HP-Cosmos, Nussdorf, German) wearing the control garments. The initial treadmill speed of 7 $km \cdot h^{-1}$ was increased by 1 $km \cdot h^{-1}$ each minute to a speed of 16 $km \cdot h^{-1}$. Thereafter treadmill gradient was increased by 2% each minute until volitional exhaustion[154]. Gradient increases were converted to equivalent demands of change in running velocity assuming an 1.5% increase in gradient of equates to an 1 $km \cdot h^{-1}$ increase in speed of as previously described[155]. To determine $v\dot{V}O_{2max,}$ the speed of the last complete stage was added to the multiplication of the speed increment by the completed fraction of the incomplete stage. Following the incremental test and a rest period of 10 minutes, participants were familiarised with the steady state condition by running on the treadmill for 5 min at 60% of their individualized $v\dot{V}O_{2max}$.

During sessions 2-4, participants initially provided a urine sample upon arrival to assess urine specific gravity (Atago Co., Ltd., Tokyo, Japan) and a 24-hour dietary intake record to confirm dietary and fluid recommendations had been adhered to. Participants were equally assigned to the control, compression or oversized condition in an attempt to balance any learning effects. For trials that required participants to wear compression tights, garment interface pressure was recorded. Following this, a standardised warm-up on a cycle ergometer (Monark 818 E, Sweden) of 5 min at 100W was undertaken.

Subsequently participants underwent a 15 min steady state (SS) running task at 60% $v\dot{V}O_{2max}$, at a gradient of 1%. The mean 60% $v\dot{V}O_{2max}$ between participants was 12.1 ± 1.3 km·h^{-1}. During the SS run, breathing frequency (BF), minute ventilation (VE) oxygen uptake ($\dot{V}O_2$) and expired carbon dioxide ($\dot{V}CO_2$) were measured constantly with a breath-by-breath gas analyser (Vyaire CPX, Mettawa, Illinois, USA). $\dot{V}O_2$ was calculated by linear interpolation between breath-by-breath $\dot{V}O_2$ data to 1 second values and then averaged over the last 3 min of the SS run task. RE was then calculated as the total volume of oxygen needed to run one kilometre relative to body mass (ml·kg^{-1}·km^{-1}) at 60% $v\dot{V}O_{2max}$. Respiratory exchange ratio (RER) was reported as the mean ratio between $\dot{V}O_2$ consumed and expired $\dot{V}CO_2$ from the final 3 min of steady state running. Heart rate was recorded throughout the run task using a wireless HR monitor (Polar S810i, Polar Electro, Finland). Participants reported RPE at 1, 3, 6, 9, 12 and 15 min using Borg's 6-20 scale [156]. To measure blood concentration of lactate ($[La^-]_b$), capillary samples from the right earlobe (20µL) were collected (Eppendorf AG, Hamburg, Germany) on completion of the SS run. Samples were analysed using a Biosen Lactate analyser (Biosen C-line analyser, EKF Industrie, Elektronik GmbH, Barbelen, Germany).

4.4.1 Data Analysis

All sets of data in the three conditions (control, compression and oversized) were initially tested for normality using the Shapiro-Wilk test. Analysis of CG interface pressure was conducted via a paired students t-test to measure potential significant differences between two means. In cases where the assumptions of normality were not met, the non-parametric Wilcoxon signed-rank test was used for comparisons of two means. VE, BF, RE, RER, HR and $[La^-]_b$ were analysed by a one-way ANOVA, with Bonferroni correction. In cases where the assumptions of normality were not met, the non-parametric Kruskal-Wallis test was used for comparisons of three conditions. Prior to conducting a repeated-measures two-way ANOVA (garment x time point) with RPE data, Mauchly's Test of Sphericity was conducted to assess variances of the differences between all combinations of related

groups. Subsequently, a Fishers LSD *post hoc* test was performed when comparisons were made across more than two levels.

RE, RER, RPE and $[La^-]_b$ was subsequently analysed for practical significance using magnitude-based inferences[157]. Statistical analysis of physiological and perceptual measures was performed using a specifically designed spreadsheet available for crossover studies[158]. We used a contemporary statistical approach because conventional statistics typically omit the magnitude of the effect, which could be considered more relevant to a therapeutic prescription than a statistically significant result[71]. Physiological data was log-transformed to reduce bias arising from non-uniformity of error and back-transformed to obtain changes in means in raw values.

The standardised effect size, (defined as (difference in mean)/standard deviation, was calculated for all variables between each clothing condition. Thresholds for small, moderate and large effects were 0.20, 0.60, and 1.20, respectively. From the spreadsheet, we used magnitude-based inferences about effect sizes (ES) and then to make inferences about true (population) values of the effect, the uncertainty in the effect was expressed as 90% confidence limits. Between-trials comparisons involved calculating the probability that the true (unknown) differences were lower than, similar to, or higher than the smallest worthwhile difference or change (0.2 x between-participant standard deviation). Quantitative chances of higher or lower differences were qualitatively ranked as follows: <1%, almost certainly not; 1-5%, very unlikely; 5-25%, unlikely; 25-75%, possible; 75-95%, likely; 95-99%, very likely and >99%, almost certain. If the chances of harm and benefit were of >0.5% and <25% respectively, the true difference was assessed as unclear. All statistical tests were processed using the statistical package SPSS (Version 18) and Microsoft Excel (Microsoft Corporation ™, Redmond, WA, USA). The level of statistical significance was identified by an alpha value of $P < 0.05$ and data reported as mean ± standard deviation (SD), unless otherwise stated.

4.5 Results

Baseline measures performed to assess the IP (mmHg) applied by the compression and oversized garment revealed significantly higher values with compression tights at the ankle (95% CI = 0.98, 2.72; p = 0.001) and thigh (95% CI = 2.06, 3.71; p = 0.003) compared with the oversized garment (Table 4-1). The IP at the posterior calf location was not significantly different (95% CI = -0.60, 3.60; p = 0.052) (Compression: ankle = 3.1 ± 1.3; calf =10.5 ± 3.1; thigh = 6.7 ± 0.6 mmHg. Oversized: ankle = 1.3 ± 0.9; calf = 9.1 ± 2.7; thigh = 3.8 ± 1.1 mmHg).

Table 4-1 Interface pressure (mmHg) with oversized (OSG) and correctly sized (CSG) compression tights for individual participants.

Participant no.	Ankle (mmHg)		Calf (mmHg)		Thigh (mmHg)	
	OSG	CSG	OSG	CSG	OSG	CSG
1	2	3	9	10	3	7
2	0	2	8	9	3	6
3	1	4	11	19	6	7
4	1	4	10	11	3	7
5	2	5	16	11	3	6
6	3	3	7	8	5	7
7	0	1	7	7	3	7
8	2	2	6	11	4	6
9	1	5	9	10	4	7
10	1	2	8	9	3	8
11	1	4	9	11	5	7
Mean ± SD	**1 ± 0.9**	**3 ± 0.9**	**9 ± 0.9**	**11 ± 0.9**	**4 ± 0.9**	**7 ± 0.9**

For RPE measures there was a significant main effect for time (F (2.2, 65.7) = 65.4, p = <0.001, η^2p = .685) but not for garment (F(2, 30) = 0.41, p = 0.960, η^2p = .003) or interaction (garment x time) (F (4.4, 65.7) = 0.208, p = 0.944, η^2p = .014).

Comparing correctly sized compression tights with the oversized condition, RPE using magnitude-based inferences revealed a *possibly beneficial* effect at 1 and 6 min (ES = -0.24 and -0.26 respectively). After 1 min of exercise, a *possible harmful* effect was reported for the oversized condition when compared with control (ES = 0.04). All further comparisons of RPE between garment conditions at each time point reported either *trivial* or *unclear* differences (Table 4-2).

Table 4-2 Between-trials comparison of rating of perceived exertion (RPE) during treadmill running at 60% $v\dot{V}O_{2max}$.

	1 min	3 min	6 min	9 min	12 min	15 min
CT (95% CL)	8.6 (7.5; 9.8)	10.1 (8.6; 11.6)	11.0 (9.6; 12.4)	11.6 (10.1; 13.2)	11.9 (10.0; 13.8)	12.6 (10.8; 14.3)
OSG (95% CL)	8.7 (7.5; 9.9)	10.1 (8.5; 11.7)	11.1 (9.7; 12.5)	11.6 (10.5; 12.8)	11.8 (10.7; 12.9)	12.4 (11.1; 13.6)
CSG (95% CL)	8.3 (7.1; 9.4)	9.8 (8.3; 11.3)	10.6 (8.9; 12.2)	11.6 (10.3; 12.8)	11.9 (10.5; 13.3)	12.5 (10.9; 14.0)
Oversized - Control						
difference in mean (90% CL) [a]	0.10 (-0.7; 0.9)	0.00 (-0.3; 0.3)	0.10 (-0.3; 0.5)	0.00 (-0.5; 0.5)	-0.09 (-0.9; 0.7)	-0.18 (-0.9; 0.5)
effect size (90% CL)	0.04 (-0.4; 0.5)	-0.02 (-0.2; 0.2)	0.04 (-0.1; 0.2)	0.04 (-0.2; 0.3)	0.04 (-0.3; 0.4)	-0.01 (-0.3; 0.3)
effect size rating	trivial	trivial	trivial	trivial	trivial	trivial
% of chances for **oversized** values to be higher / trivial / lower than **control**	25/59/16	2/95/3	6/92/1	10/87/4	19/72/9	11/74/14
rating **oversized** vs **control** [b]	Possibly harmful	Likely trivial	Likely trivial	Likely trivial	Possibly trivial	Possibly trivial
Compression - Control						
difference in means (90% CL) [a]	-0.40 (-0.9; 0.2)	-0.30 (-0.8; 0.3)	-0.50 (-1.2; 0.3)	-0.10 (-0.8; 0.6)	0.00 (-0.6; 0.6)	-0.09 (-0.9; 0.7)
effect size (90% CL)	-0.20 (-0.5; 0.1)	-0.12 (-0.4; 0.1)	-0.22 (-0.6; 0.1)	0.00 (-0.3; 0.3)	0.04 (-0.2; 0.2)	-0.01 (-0.3; 0.3)
effect size rating	small	trivial	small	trivial	trivial	trivial
% of chances for **compression** values to be higher / trivial / lower than **control**	2/47/50	2/69/29	2/44/54	10/79/11	9/88/2	10/77/13
rating **compression** vs **control** [b]	Unclear	Unclear	Unclear	Likely trivial	Likely trivial	Likely trivial
Compression - Oversized						
difference in means (90% CL) [a]	0.50 (-1.0; 0.1)	-0.30 (-1.0; 0.4)	-0.50 (-1.3; 0.2)	-0.10 (-0.8; 0.6)	0.09 (-0.6; 0.8)	0.09 (-0.8; 1.0)
effect size (90% CL)	-0.24 (-0.5; 0.0)	-0.11 (-0.4; 0.2)	-0.26 (-0.6; 0.1)	-0.04 (-0.3; 0.2)	0.00 (-0.2; 0.2)	0.00 (-0.3; 0.4)
effect size rating	small	trivial	small	trivial	trivial	trivial
% of chances for **compression** values to be higher / trivial / lower than **oversized**	0/38/62	6/63/31	1/36/63	7/78/16	7/86/2	16/68/16
rating **compression** vs **oversized** [b]	Possibly beneficial	Unclear	Possibly beneficial	Likely trivial	Likely trivial	Possibly trivial

[a] Between garment mean difference (90% confidence limit); [b] Qualitative descriptor. CT, control clothing; OSG, oversized garment; CSG, correctly sized garment.

Running economy was not significantly different between compression (207.4 ±10.8 ml·kg^{-1}·km^{-1}), oversized (211.2 ±10.3 ml·kg^{-1}·km^{-1}) and control (214.2 ±11.6 ml·kg^{-1}·km^{-1}) as determined by one-way ANOVA ($F(2,30) = 1.074$, $p = 0.35$). There was a small and *likely beneficial* effect of compression tights on running economy when comparing compression with control (0:5:95%; ES = -0.55) during steady state exercise (Table 4-3). The individual response to compression is highlighted in Figure 4-2. No differences in body mass were observed between garment conditions ($F(2,30) = 0.007$, $p = 0.99$), indicating that changes in running economy are not related to the changes in body mass. The effect size for running economy between oversized and control, plus compression and oversized was small (ES = -0.24 and -0.32 respectively), with *unclear* inferences.

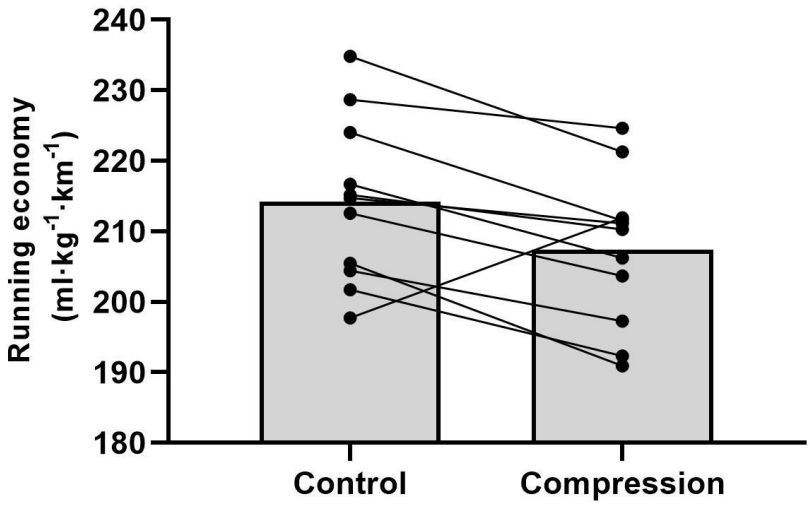


Figure 4-2 *The individual and mean running economy response with correctly fitted compression compared to control during treadmill running at 60% v$\dot{V}O_{2max}$.*

There was no significant difference ($F(2,30) = .343$, $p = 0.71$) in mean RER between compression (0.91 ± 0.3), oversized (0.90 ± 0.4) and control (0.91 ± 0.3). When compared with the oversized garment, compression produces a small and *possibly harmful* effect (60:31:9%; 0.29) on RER. Additional RER comparisons between garment conditions produced unclear inferences. Following steady state exercise, there were no significant differences in $[La^-]_b$, with trivial effect sizes, and

unclear inferences (Table 4-2). Due to signalling interruptions with the HR monitors, complete data was only collected for seven participants. Furthermore, data was incomplete and interpolation of VE and BF was not possible for one participant. There was no significant effect of garment condition in HR, VE and BF ($F(2,15) = .207$, $p = 0.82$; $F(2,27) = .0.62$, $p = 0.94$ and $F(2,27) = .0.21$, $p = 0.98$, respectively). There were *unclear* or *trivial* inferences regarding compression on HR, VE and BF (Table 4-4).

Table 4-3 Between trials comparison of running economy, respiratory exchange ratio (RER) and blood lactate values during treadmill running at 60% $v\dot{V}O_{2max}$

	Economy	RER	Blood lactate [c]
	($ml \bullet kg^{-1} \bullet km^{-1}$)		(mmol•L)
CT (95% CL)	214.2 (206.4; 222.0)	0.91 (0.89; 0.93)	2.97 (2.25; 3.69)
OSG (95% CL)	211.2 (204.3; 218.2)	0.90 (0.87; 0.92)	2.90 (2.23; 3.58)
CSG (95% CL)	207.4 (200.1; 214.6)	0.91 (0.88; 0.93)	2.86 (2.16; 3.56)
Oversized - Control			
difference in mean (90% CL) [a]	-3.00 (-8.0; 2.0)	0.01 (0.0; 0.0)	-0.07 (-0.4; 0.2)
effect size (90% CL)	-0.24 (-0.7; 0.2)	-0.35 (-0.9; 0.2)	-0.11 (-0.5; 0.3)
effect size rating	small	small	trivial
% of chances for **oversized** values to be higher / trivial / lower than **control**	4/40/56	5/26/69	8/60/32
rating **oversized** vs **control** [b]	Unclear	Unclear	Unclear
Compression - Control			
difference in means (90% CL) [a]	-6.80 (-11.1; -2.5)	0.00 (0.0; 0.0)	-0.11 (-0.5; 0.2)
effect size (90% CL)	-0.55 (-0.9; -0.2)	-0.06 (-0.6; 0.5)	-0.13 (-0.5; 0.3)
effect size rating	small	trivial	trivial
% of chances for **compression** values to be higher / trivial / lower than **control**	0/5/95	19/50/32	8/56/37
rating **compression** vs **control** [b]	Likely beneficial	Unclear	Unclear
Compression - Oversized			
difference in means (90% CL) [a]	-3.80 (-9.8; 2.1)	0.01 (0.0; 0.0)	-0.04 (-0.4; 0.3)
effect size (90% CL)	-0.32 (-0.8; 0.2)	0.29 (-0.3; 0.9)	-0.02 (-0.4; 0.4)
effect size rating	small	small	trivial
% of chances for **compression** values to be higher / trivial / lower than **oversized**	4/30/66	60/31/9	15/64/20
rating **compression** vs **oversized** [b]	Unclear	Possibly harmful	Possibly trivial

[a] Between garment mean difference ± 90% confidence limit; [b] Qualitative descriptor; [c] Assumption of normality not met therefore analysed with Kruskal-Wallis test

Table 4-4 Between trials comparison of heart rate (HR), minute ventilation (VE) and breathing frequency (BF) during treadmill running at 60% $v\dot{V}O_{2max}$

	HR *(n=6)*	VE *(n=10)*	BF *(n=10)*
	(bpm)	L/min	(1/min)
CT (95% CL)	170 (163; 177)	92.8 (79.2; 106.3)	42.8 (36.4; 49.1)
OSG (95% CL)	171 (164; 177)	90.0 (77.7; 102.2)	43.5 (38.0; 49.0)
CSG (95% CL)	168 (160; 176)	91.0 (78.3; 103.7)	43.2 (37.7; 48.7)
Oversized - Control			
difference in mean (90% CL) [a]	-0.26 (-2.0; 2.5)	-2.79 (-5.9; 0.3)	-0.74 (-1.3; 2.7)
effect size (90% CL)	-0.03 (-0.2; 0.3)	-0.12 (-2.7; 0.0)	-0.10 (-0.1; 0.3)
effect size rating	trivial	trivial	trivial
% of chances for **oversized** values to be higher / trivial / lower than **control**	14/78/08	0/82/18	19/80/1
rating **oversized** vs **control** [b]	Likely trivial	Likely trivial	Likely trivial
Compression - Control			
difference in means (90% CL) [a]	-1.94 (-5.1; 1.2)	-1.78 (-3.4; -0.2)	-0.41 (-1.1; 1.9)
effect size (90% CL)	-0.25 (-0.6; -0.2)	-0.08 (-0.2; 0.0)	-0.06 (-0.1; 0.2)
effect size rating	small	trivial	trivial
% of chances for **compression** values to be higher / trivial / lower than **control**	4/38/59	0/99/1	7/93/1
rating **compression** vs **control** [b]	Unclear	Very likely trivial	Likely trivial
Compression - Oversized			
difference in means (90% CL) [a]	-2.21 (-4.7; 0.3)	1.01 (-1.3; 3.3)	-0.33 (-2.0; 1.3)
effect size (90% CL)	-0.28 (-0.6; 0.0)	0.05 (-0.0; 0.2)	-0.03 (-0.2; 0.1)
effect size rating	small	trivial	trivial
% of chances for **compression** values to be higher / trivial / lower than **oversized**	1/30/68	1/98/0	1/95/4
rating **compression** vs **oversized** [b]	Unclear	Very likely trivial	Likely trivial

[a] Between garment mean difference ± 90% confidence limit; [b] Qualitative descriptor

4.6 Discussion

In the present study, we assessed the influence of correctly fitted and oversized, non-graduated compression tights on parameters of submaximal running, metabolic response and ratings of perceived exertion. The major finding is that during steady state running at 60% $v\dot{V}O_{2max}$, correctly fitted compression tights that elicit an interface pressure <15 mmHg are *likely beneficial* in improving RE when compared with running shorts. We provide new evidence that low-pressure sports compression tights, applying the greatest interface pressure at the calf, elicit a small yet beneficial influence on RE. Only *possible*, *trivial* or *unclear* differences were observed in all other measures, with either small or trivial effect sizes.

4.6.1 Influence of Compression Tights on Running Economy

Running at a velocity of ~12 km·h^{-1} with compression tights produces a mean improvement in RE of 3.2%. This improvement is comparable to a 6 week interval or continuous training period[159]. In the investigation implementing interval training, a 3.0% improvement in RE was reported when repeated 4-6 x 4 min bouts at 106% vVO2max was completed (3 d/wk for 6 wk) by recreational runners. In the same investigation, a separate group of participants underwent continuous training at 94% $v\dot{V}O_{2max}$ (3 d/wk for 6 wk) and produced a 3.1% improvement in RE. Interestingly, a third group of participants trained at 132% v$\dot{V}$O2max, yet did not elicit an improvement in RE. However, unlike the current study, 6 weeks of interval or continuous training brought about additional physiological adaptations such as a reduction in blood lactate and HR when running at ~13.8 km·h^{-1}. In the present investigation, the acute donning of compression produced no change in blood lactate, RER, HR, BF or VE, suggesting that the observed alteration in running economy is more likely due to biomechanical factors than physiological. Had a reduced VE, HR or greater carbohydrate utilisation during oxidative phosphorylation been identified, this would have been suggestive of a decreased cardiorespiratory cost, however this was not observed in this instance. An alternative theory, whilst not explored in the present study, is that compression leads to an alteration in running technique. Compression sleeves (ankle to thigh) have been shown to reduce stride length when running at 10 and 14 km·h^{-1} [160].

However, the pressure applied by the garments to elicit a reduction in stride length was significantly higher than those used in the present study (33.4 and 20.4 mmHg at the calf and thigh respectively). In the same investigation, garments applying a lower level of pressure, yet approximately twice the pressure applied by the compression tights in the present study (23.2 and 10.8 mmHg at the calf and thigh respectively) did not elicit a significant effect on stride length compared with the control condition. However, despite the lack of statistical significance, a pressure:stride length interaction was apparent, with low pressure garments causing a small reduction in stride length (2.2 and 1.7 cm at 10 and 14 $km \cdot h^{-1}$ respectively). It is conceivable that CGs may limit range of motion at the transverse and frontal planes of the trunk and hip, thereby stabilising the pelvis at the time of foot impact with the ground. A reduction in active range of motion (AROM) during hip flexion with compression shorts supports this notion [74,75]. If indeed, the *likely beneficial* effect of compression tights is due to the reduced AROM at the hip and subsequent alteration to stride length, only tight fitting shorts or tights will elicit this physiological response. In support of this, compressive calf stockings (ankle to below knee) caused no change in stride length, contact time, flight time or stride frequency at 105% of a recent 10 km running performance (~17 $km \cdot h^{-1}$) during a time to exhaustion test [81]. Additionally, well-trained distance runners reported no change in running gait variables, nor running economy when running at 14, 16 and 18 $km \cdot h^{-1}$ compared to running shorts [94]. Again, the garments worn were calf stockings, therefore no pressure is applied to the hip region, and hence gait is unlikely to be influenced. Furthermore, well-trained distance runners would possess a well-developed running economy and are less likely to benefit from the application of CGs, already possessing an established, economically optimal locomotion style. The participants in the present study were recreationally active individuals ($\dot{V}O_{2max}$ = 54 $ml \cdot kg^{-1} \cdot min^{-1}$), lacking an optimised, highly economical running style. As such, compression tights may produce a *likely beneficial* effect on RE as a result of reducing excessive range of motion and metabolically expensive stabilising muscular activity [161].

4.6.2 Influence of Compression Tights on Rating of Perceived Exertion

In the current study, RPE was similar for all garment conditions when running at 60% v$\dot{V}O_{2max}$. These findings are comparable to others when long tights are worn during submaximal running exercise [9,126]. Despite some authors reporting a reduced RPE during submaximal running when wearing lower body compression clothing [154,162], it is not possible to truly blind participants to the garment condition, therefore the role of expectations may influence the perceived experience. CGs have been shown to influence perception of exertion during steady state cycling at 60% peak power output [163]. Participants were shown a 3 min video clip prior to exercise to influence their expectation of a sleeveless compression shirt. When participants had a more positive expectation, a reduced perception of exertion was experienced.

4.6.3 The Role of Varying Interface Pressure

Correctly sized and oversized garments were used to investigate whether a pressure dose-response existed. When compared with medical compression classifications [26], both garments apply low pressure at the three anatomical locations. The reduced energy cost observed in the present investigation is comparable to that of previous studies [9,81]. However limited information is available regarding the interface pressures, with one study failing to report any pressure values [9] and the other reporting ankle pressure (15 – 22 mmHg) but fails to document how this information was collected [81]. Opposing results demonstrate no change in oxygen consumption during a submaximal run at 70% $\dot{V}O_{2max}$ with compression stockings, long tights or compression shorts with a garment interface pressure targeted at 20 mmHg [8]. In addition, no change in oxygen consumption was reported wearing compression tights during a submaximal run at a speed equivalent to the first ventilatory threshold (VT_1). The long tights in this study were the same brand as the present study and interface pressures were 13.6 and 8.6 mmHg at the calf and thigh respectively; however participants exercised in either a cold 10°C, or hot 32°C environment, unlike the ambient conditions implemented in the present study. In the absence of a defined, optimal sports compression interface pressure [142], a minimum threshold to improve venous return of 17 and 15 mmHg at the calf and thigh respectively

is proposed [12]. The compression tights used in the present study did not surpass this minimum threshold and as such, without a change in venous return, it is unlikely the current, low-pressure tights will influence cardiac parameters. Furthermore, despite statistically significant differences in interface pressure reported between the two garments, this difference in practical terms is likely to be unimportant. It is conceivable that while the CGs apply similar interface pressures, the oversized garment may offer less support around the hip and knee joint, or places on the garment where stitching is located and act as anchor points for the garment during dynamic movement. Anecdotally, some participants reported the oversized garment felt loose around the crotch. This may have led to restricted hip flexion, requiring greater perceived effort to overcome this restriction.

The varied interface pressure applied by CGs offers a plausible explanation for the conflicting results observed in the sports compression literature. The variation in interface pressure testing and measurement devices has previously been discussed (Chapter 3), indicating that even when pressures are recorded, the absolute pressure values are dependent on the anatomical location of the measurement and the specific type of measurement device. In light of this, caution should be taken when directly comparing published interface pressures from varying devices, or from values that are 'advised' by the CG manufacturers.

The present study demonstrated that non-graduated, compression tights, applying a low interface pressure (6 - 15 mmHg), produce a greater benefit compared with an over-sized garment. This suggests that a minimum interface pressure threshold may exist, whereby interface pressure below a particular value may not stimulate muscle or skin mechanoreceptors sufficiently. As a result, minimally compressive garments may not elicit sufficient afferent feedback to assist with reducing excessive range of motion or assisting with optimised proprioception in recreational runners.

4.6.4 Practical Application

The running speed at 60% v$\dot{V}O_{2max}$ corresponded to a relative intensity of 79.4 ± 6% VO_{2max}. Previous research identified that recreational half-marathon runners typically perform at this relative intensity [164] and running at 80% $\dot{V}O_{2max}$ for 90 minutes causes a gradual increase in running economy [165].

Strategies to reduce or attenuate the increase in oxygen consumption over a prolonged submaximal run are advantageous for recreational runners.

Wearing non-graduated, low pressure (<15 mmHg), lower body compression tights during submaximal running leads to a reduction in oxygen cost of ~3% in the final 3 min of a 15-minute steady-state protocol. The present results provide evidence that compression tights may be beneficial to distance runners, since small improvements in running economy become important over long distances. A 5% improvement in running economy induced approximately 3.8% increase in distance running performance[6]. Future studies are required to elucidate the mechanisms integrating with the observed improvement in running economy, plus identify if these physiological changes translate into a measurable performance enhancement.

Despite the *likely beneficial* effect of compression tights on RE observed in this study, data was obtained in a controlled laboratory environment. The applicability of these findings to over-ground running requires further exploration. Since air and wind resistance are not a factor during laboratory testing, and running technique differ between treadmill and road, transferring treadmill data to over-ground running requires caution [110].

The observed reduction in oxygen cost in the present study was 3.2%. The intra-individual variation of running economy is reported to vary between 1.3 – 5% at speeds of 12 – 18 $km \cdot h^{-1}$ [166,167]. Therefore, the reported *likely beneficial* effect of compression on RE could be due to variation in technical and biological variation. However, Periera *et al.,* [166] revealed a RE coefficient of variation of 2.0% with participants of a very similar aerobic capacity and training status to the current study. Furthermore, the time of testing, prior exercise, pre-exercise dietary intake, footwear and environmental conditions were well controlled with each participant in the current study, thus minimising possible variables that might negatively impact the intra-individual variation.

4.7 Conclusion

In conclusion, the results of this study reveal an improved running economy when running on a treadmill at ~12 km·h^{-1} with correctly fitting compression tights, eliciting a non-graduated design with low interface pressures (<15 mmHg). It seems possible that wearing compression tights during running may positively influence the non-optimised running technique of recreationally active males. However, the extent to which compression tights improve running economy requires further investigation with reference to alternative running intensities and varying garment interface pressures.

5 The influence of compression tights on running economy varies by relative intensity

5.1 Rationale

Correctly fitted compression tights produce a small yet likely beneficial effect on running economy at a specific running intensity. Further investigation is required to explore the role of compression tights across a wider spectrum of relative exercise intensities. Furthermore, an appropriately powered investigation will provide the opportunity to build upon the initial findings of Chapter 4. Running economy is reported as caloric unit cost rather than oxygen cost, thus offering greater insight into potential alterations in substrate utilisation during submaximal running with and without correctly sized compression tights.

5.2 Abstract

The effect of compression tights on running economy (RE) is unclear. The purpose of this investigation was to assess the influence of compression tights on RE and substrate utilisation across a range of exercise intensities (67.1 – 91.5% $\dot{V}O_{2max}$). Twenty-six recreationally active males ran for 15 min with compression tights and a non-compression control condition. Oxygen consumption ($\dot{V}O_2$) and expired carbon dioxide ($\dot{V}CO_2$) was measured to determine RE as caloric unit cost, carbohydrate oxidation (CHO_{OX}) and fat oxidation (FAT_{OX}). No difference was observed between conditions for RE, CHO_{OX} or $FAT_{OX,}$ however relative exercise intensity (%$\dot{V}O_{2max}$) correlated with ΔRE (r = -0.501, P < 0.01). Receiver operator curve analysis revealed that %$\dot{V}O_{2max}$ is a sensitive and specific predictor of altered RE. Above 77.7% $\dot{V}O_{2max}$, compression led to significantly lower RE (p < 0.05), whereas no difference between conditions was observed below 77.7% $\dot{V}O_{2max}$. These data suggest that compression tights influence RE dependant on relative exercise intensity when $\dot{V}O_{2max}$ (%) is used as an anchor of exercise intensity.

5.3 Introduction

Running economy (RE) defined as the metabolic cost of travelling a given distance is a useful indicator of endurance performance [168]. RE is a stronger predictor of performance than maximal oxygen consumption ($\dot{V}O_{2max}$) within homogenous populations [169] and small differences in metabolic cost of running can differentiate performance between elite runners with comparable $\dot{V}O_{2max}$ and metabolic potential [170]. RE is modulated by metabolic, cardiopulmonary, biomechanical and neuromuscular factors [110]. The effects of compression on metabolic [10,41], cardiopulmonary [171], neuromuscular [114] and biomechanical [81,94] systems from CGs may all contribute to improvements in RE [4] .

Data on the effect of compression tights on submaximal RE are limited to just two investigations both reporting RE as the volume of oxygen required to run a given distance relative to body mass (i.e. $ml \cdot kg^{-1} \cdot km^{-1}$) [9,10]. There was no difference in economy when running at 10, 14 or 16 $km \cdot h^{-1}$. Compression improved RE only when running at 12 $km \cdot h^{-1}$ and also reduced the amplitude of oxygen uptake at 80%$\dot{V}O_{2max}$ [9]. Dascombe *et al*., found no difference at running velocities above 8 $km \cdot h^{-1}$ [10]. It is suggested that divergent results are due to the training status of participants and the level and spatial distribution of pressure applied by compression tights [36]. Furthermore, inconsistencies might be due to the relative insensitivity of measures used to report RE. Studies typically report economy as the oxygen cost of running per unit distance ($ml\ O_2 \cdot kg^{-1} \cdot km^{-1}$) or per unit of time ($ml\ O_2 \cdot kg^{-1} \cdot min^{-1}$)[9,10]. However, oxygen cost is less sensitive to changes in relative speed [11,110,168] compared with energy cost reported as the caloric unit cost ($kcal \cdot kg^{-1} \cdot km^{-1}$). Caloric unit cost accounts for substrate dependent variations in energy equivalent of a volume of oxygen [11], thereby adjusting for different substrate use at submaximal speeds.

In light of the limited evidence, an interaction between exercise intensity and RE is apparent when wearing compression tights. This interaction requires further investigation and is the primary goal of

the present study. It was therefore hypothesised that at higher relative exercise intensities, RE would be improved with compression tights. The aim of the present study was to examine whether compression tights modify running economy reported as caloric unit cost and substrate use in recreationally trained individuals. The second aim was to investigate the interaction between relative exercise intensity and RE with and without compression tights.

5.4 Methods

5.4.1 Participants

Ethical approval was received from the University of Essex ethical committee. Participants provided written informed consent in accordance with the Declaration of Helsinki. Sample size estimation was based on expected differences in RE either with and without compression tights [10]. The *ES* in this study was 0.76. With an alpha = .05 and power = 0.90, the estimated sample size needed with this effect size is approximately *n*=21. Twenty-six healthy male volunteers provided written informed consent before participation in the study (Table 5-1). All participants were physically active, participating in sport specific training sessions a minimum of three times per week and free from musculoskeletal injury within the one month previous.

Table 5-1 Descriptive characteristics of participants (*n* = 26)

	Mean [95%CI]
Age (years)	27.9 [25.1-30.7]
Height (m)	1.79 [1.76-1.81]
Body Mass (kg)	76.1 [72.7-79.5]
BMI ($kg \cdot m^{-2}$)	23.8 [23.0-24.6]
$\dot{V}O_{2max}$ ($ml \cdot kg \cdot^{-1} min^{-1}$)	54.7 [52.8-56.7]
$v\dot{V}O_{2max}$ (km^{-1})	18.7 [18.2-19.2]

5.4.2 Compression garments

The CG used in the investigation were Skins ™ Men's Compression A400 Long Tights (Riverwood, Australia). Garment size was selected in accordance with the manufacturer's sizing guide. The garments were made from warp knitted fabrics, with the fibre reported as 76% nylon and 24% elastane. The pressure exerted by the CGs on the lower limbs were evaluated by the PicoPress® (Microlabs, Italy) pressure monitor (coefficient of variation = <5% at 20 mmHg [1]). Chapter 3 revealed the PicoPress is a suitable pneumatic pressure monitor. Pressure measures were recorded at two anatomical locations (posterior orientation of the maximal calf girth and anterior thigh at the mid-point between mid-trochanterion-tibiale laterale). The control condition consisted of loose fitting running shorts, thereby providing a comparison between compression tights and garments typically worn by recreational runners. The same short sleeve top and running shoes were worn on every testing occasion.

5.4.3 Experimental design

Participants were required to attend on three occasions separated by at least one week. At visit 1 participants performed an incremental treadmill test to determine $\dot{V}O_{2max}$ and peak running speed ($v\dot{V}O_{2max}$). This was followed by a 5-min familiarisation at a relative intensity corresponding to 60-65% $v\dot{V}O_{2max}$. Compression and control conditions were performed during visits 2 and 3 in a randomised, counter-balanced order, during which participants completed a 15 min submaximal treadmill task.

Each participant attended the laboratory (temperature: 18 ± 1.0° C) at the same time each visit to minimise variation in physiological parameters that might change with circadian rhythm. In the 24 hours prior to testing, participants were asked to refrain from exercise, caffeine and alcohol intake. Participants were asked to record their diet for the 24 hours before the initial laboratory visit and to repeat this for all subsequent visits. To ensure running economy was not influenced by dehydration, participants were recommended to consume fluid the night before and the morning of testing in accordance with fluid intake recommendations[172] . Participants provided a urine sample on arrival

of each session and urine specific gravity (USG) was measured (Atago Co., Ltd., Tokyo, Japan). Participants only began exercise when USG indicated euhydration (USG <1.020). Two hours prior to testing, no food and only water were consumed.

5.4.4 Establishing individual aerobic capacity

Respiratory gases were collected continuously throughout the incremental test. Participants wore a dead-space mask with an impeller turbine assembly (Hans Rudolph, Kansas, USA) and gas concentrations continuously sampled via a capillary line. Concentrations were determined by electrochemical (O_2) and infrared (CO_2) analysers (Vyaire CPX, Mettawa, Illinois, USA). Prior to each test, the gas analysers were calibrated with gases of known concentration (16% O_2 and 5% CO_2), and ambient air. The digital volume transducer was connected to the housing blower and calibrated automatically using both high and low flow parameters.

Participants completed an incremental exercise test on a motorized treadmill (Quasar; HP Cosmos, Nussdorf, Germany). The protocol began at 7 km·h^{-1}, after which the speed increased by 1 km·h^{-1} every minute up to 16 km·h^{-1}. At 16 km·h^{-1}, workload increments continued by increasing the gradient 2% each minute until volition exhaustion. To determine v$\dot{V}O_{2max}$, a gradient increase of 1.5% was converted to an equivalent increase in speed of 1 km·h^{-1} [155]. The calculated speed of the last complete stage was added to the multiplication of the speed increment by the completed fraction of the incomplete stage. $\dot{V}O_{2max}$ was determined as the highest 30 s average oxygen consumption.

5.4.5 Submaximal running economy assessment

Participants ran for 15-min at a speed corresponding to 63 ± 2% v$\dot{V}O_{2max}$ (70-90% $\dot{V}O_{2max}$) and gradient remained at 1% throughout. Participants ran at the same speed in both sessions, with only the garment condition changing.

5.4.6 Data treatment

Breath-by-breath data were converted to second-by-second data using linear interpolation. Oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) were averaged over the final 3 min of each

submaximal exercise test. Second-by-second $\dot{V}O_2$ and $\dot{V}CO_2$ data were used to determine running economy (RE) as caloric unit cost ($kcal \cdot kg^{-1} \cdot km^{-1}$), carbohydrate oxidation (CHO_{OX}) and fat oxidation (FAT_{OX}) ($g \cdot kg^{-1} \cdot km^{-1}$) using equations for moderate to high intensity (50-75% $\dot{V}O_{2max}$) [173]. Equations for the calculation of energy expenditure and oxidation of carbohydrate and fat from gas exchange measurements are displayed below;

Energy expenditure ($kcal \cdot min^{-1}$) = $0.550 \cdot \dot{V}CO_2 + 4.471 \cdot \dot{V}O_2$

Carbohydrate oxidation ($g \cdot min^{-1}$) = $4.210 \cdot \dot{V}CO_2 – 2.962 \cdot \dot{V}O_2$

Fat oxidation ($g \cdot min^{-1}$) = $1.695 \cdot \dot{V}CO_2 – 1.701 \cdot \dot{V}O_2$

Expressed to distance (i.e. $kcal \cdot km^{-1}$) = ($kcal \cdot min^{-1}$ * 60) / $km \cdot h^{-1}$

Expressed to body mass (i.e. $kcal \cdot kg^{-1} \cdot km^{-1)}$ = $kcal \cdot km^{-1}$ / body mass (kg)

To ensure principally aerobic contribution to energy expenditure, we excluded participants if respiratory exchange ratio (RER) >1.00 during the final 3 min of the submaximal run.

5.4.7 Statistical analysis

Data are presented as mean and 95% confidence intervals (95%CI) for all dependent variables. Normality of distribution was assessed using the Shapiro-Wilk test. Paired t-tests were used to analyse mean differences in RE, CHO_{OX} FAT_{OX} between conditions. Cohen's *d* was calculated as a measure of effect size [174]. We interpreted values of d=0.2, d=0.5, and d=0.8 as a small, moderate or large effect size.

We calculated the difference in RE ($\Delta kcal \cdot kg^{-1} \cdot km^{-1}$) between conditions (compression – control) for caloric unit cost and used Pearson's product-moment correlation to examine associations with relative ($\%\dot{V}O_{2max}$) and absolute exercise intensity (running speed [$km \cdot h^{-1}$]). Receiver operator curve (ROC)

analysis was used to establish threshold values of $\%\dot{V}O_{2max}$ which identify compression tights as producing a potential ergogenic outcome on running economy. Youden index (*J*) was the preferred method to determine the optimal cut-off point of the ROC analysis[175]. *J* is defined as the maximum vertical distance between the ROC curve and the diagonal or chance line (*J* = sensitivity – specificity - 1), therefore the point at which the cut-off threshold is farthest from chance [176]. Statistical tests were processed using the statistical package SPSS (Version 18) and Microsoft Excel (Microsoft Corporation TM, Redmond, WA, USA). The level of statistical significance was identified by an alpha value of $P < .05$.

5.5 Results

Interface pressure applied by compression tights was 8.9 [7.8 - 9.9] mmHg at the calf and 6.8 [6.3, 7.3] mmHg at the thigh. During the submaximal RE assessment all participants maintained a RER <1.00 and were included in the analysis.

Table 5-2 shows no difference for $\%\dot{V}O_{2max}$, RE, CHO_{OX} and FAT_{OX} ($P > 0.05$) between the control and compression condition.

Table 5-2 Running economy and substrate utilisation data during a submaximal run with and without compression tights (Mean [95% CI]).

	Control	Compression	*P*-value	*d*=
$\%\dot{V}O_{2max}$	77.5 [74.7-80.2]	76.8 [74.5-79.2]	0.33	0.19
RE ($kcal \cdot kg^{-1} \cdot km^{-1}$)	1.08 [1.05-1.11]	1.07 [1.04-1.10]	0.38	0.18
CHO_{OX} ($g \cdot kg^{-1} \cdot km^{-1}$)	0.19 [0.18-0.20]	0.18 [0.17-0.20]	0.22	0.25
FAT_{OX} ($g \cdot kg^{-1} \cdot km^{-1}$)	0.03 [0.03-0.04]	0.03 [0.03-0.04]	0.43	0.16

d = Cohen's effect size; RE = caloric unit cost; CHO_{OX} = carbohydrate oxidation; FAT_{OX} =fat oxidation. Mean [range] running speed the same in both conditions = 11.7 [10.0 - 14.5] $km \cdot h^{-1}$.

The range of relative exercise intensity was 67.1 – 91.5 %$\dot{V}O_{2max}$ during the control condition and between 68.6 – 89.9 %$\dot{V}O_{2max}$ with compression. Figure 5-1 shows the difference in RE (Δkcal·kg^{-1}·km^{-}1) between garment conditions was negatively correlated with relative exercise intensity (%$\dot{V}O_{2max}$).

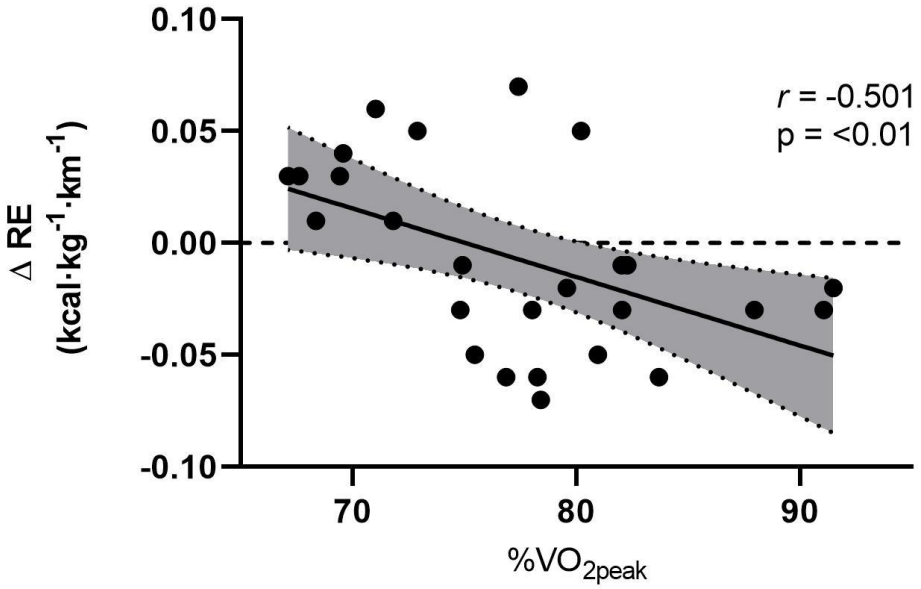


Figure 5-1 *Correlation and 95% confidence interval (shaded area) between relative exercise intensity measured during the control condition (%$\dot{V}O_{2max}$) and ΔRE.*

ROC analysis area under curve value was AUC= 0.925, (95%CI: 0.814 – 1.0; *J* = 0.650). The cut-off value that best determined the presence or absence of a change in outcome was 77.7% $\dot{V}O_{2max}$. Table 5-3 shows group means for RE and substrate utilisation for participants split according to relative exercise intensity of </>77.7% $\dot{V}O_{2max}$. Compression tights improved RE above 77.7% $\dot{V}O_{2max}$ by 0.028 kcal·kg^{-1}·km^{-1} (*d = 0.93*) compared with control values. Whereas no difference in RE or substrate utilisation was apparent below 77.7% $\dot{V}O_{2max}$ (difference = 0.014 kcal·kg^{-1}·km^{-1}; *d = 0.34*).

Table 5-3 Comparisons in running economy, carbohydrate and fat oxidation between participants who ran above and below 77.7% $\dot{V}O_{2max}$ with and without compression tights (Mean [95% CI]).

	%$\dot{V}O_{2max}$ <77.7% (*n*=13)			%$\dot{V}O_{2max}$ >77.7% (*n*=13)		
	Control	Compression	*d*	Control	Compression	*d*
RE ($kcal \cdot kg^{-1} \cdot km^{-1}$)	1.051 [1.013-1.089]	1.065 [1.022-1.107]	*d*=0.34	1.103 [1.057-1.150]	1.075 [1.029-1.121]	*d*=0.93
CHO_{OX} ($g \cdot kg^{-1} \cdot km^{-1}$)	0.176 [0.156-0.197]	0.165 [0.147-0.184]	*d*=0.43	0.203 [0.191-0.216]	0.202 [0.185-0.219]	*d*=0.06
FAT_{OX} ($g \cdot kg^{-1} \cdot km^{-1}$)	0.034 [0.026-0.042]	0.040 [0.032-0.048]	*d*=0.46	0.028 [0.023-0.033]	0.026 [0.018-0.034]	*d*=0.24

d = Cohen's effect size; RE = caloric unit cost; CHO_{OX} = carbohydrate oxidation; FAT_{OX} =fat oxidation.

5.6 Discussion

The influence of compression tights on running economy varies according to the relative intensity of exercise. Expressed as caloric cost of exercise, running economy was improved by compression, but meaningful effects were restricted to exercise intensities >77.7% $\dot{V}O_{2max}$. Our investigation provides a new view on the influence of compression tights on RE when reported as caloric unit cost.

At higher (>77.7% $\dot{V}O_{2max}$) intensities, compression appears to enhance RE, without altering substrate utilisation. The improved RE at a higher relative exercise intensity supports previous findings revealing that compression stockings produce a positive effect on RE at 80 and ~90% $\dot{V}O_{2max}$ [9,81]. In agreement with previous compression studies, no difference in RE or substrate utilisation was observed when garment conditions were compared as a whole group (67.1 – 91.5% $\dot{V}O_{2max}$) [126] or below 77.7% $\dot{V}O_{2max}$ [46,47,58].

Compression studies typically express economy as oxygen cost per unit of distance ($ml \cdot kg^{-1} \cdot km^{-1}$). Describing the VO_2 related to a particular velocity provides a useful measure for within-participant comparisons of different conditions. VO_2 may lack sensitivity as it does not account for differences in substrate use at any given speed[168]. Economy can also be expressed as caloric unit cost ($kcal \cdot kg^{-1} \cdot km^{-1}$). This metric is more sensitive to changes in running speed and differences in substrate use [11]. Better sensitivity makes it a better choice when investigating interventions known to cause small changes in economy such as compression. Unlike oxygen cost, caloric unit cost also provides information on substrate utilisation. Despite this, previous compression studies have only reported RE as the oxygen cost. The present study is the first to explore the role of compression tights on caloric unit cost.

Above 77.7% $\dot{V}O_{2max}$, RE in the compression condition was 0.03 $kcal \cdot kg^{-1} \cdot km^{-1}$ lower compared with control. It is important to compare the observed differences in RE with the typical day-to-day variation to evaluate the extent in which the observed change is meaningful. The typical error (TE) of energy cost ($kcal \cdot kg^{-0.75} \cdot km^{-1}$) in highly trained runners is 3.14% [177]. We report an improvement in RE of 2.6% in the compression condition at a relative exercise intensity above 77.7% $\dot{V}O_{2max}$ when scaling body mass to a power function exponent of $^{-0.75}$ (control = 3.250 ± 0.19; compression = 3.169 ± 0.21 $kcal \cdot kg^{-0.75} \cdot km^{-1}$). However, the reported TE was observed in the absence of dietary and training constraints. It is plausible that the standardisation of clothing, footwear, dietary and training factors in the present study would contribute toward a lower TE. Owing to no other comparative TE measures available for caloric unit cost during treadmill exercise, interpreting the magnitude of the observed difference requires conversion to an alternative unit of energy expenditure ($kJ \cdot min^{-1}$). By doing so we report a difference in energy expenditure of 2.5% between garment conditions above 77.7% $\dot{V}O_{2max}$. The within and between-day coefficient of variation for energy expenditure at 70% $\dot{V}O_{2max}$ is between 1.7% [178] and 2.2% [179], therefore the improved energy expenditure reported with compression tights can be considered real and worthwhile [180].

Similar improvements in RE have been observed following 8 weeks of high intensity interval training [181], 6 weeks of plyometric training [182] and 4 weeks of living and training at altitude [183]. However, chronic training interventions that demonstrate an improvement in RE are also likely to elicit a number of physiologic adaptations that contribute toward improved distance running performance. Conversely, when an improved RE is observed with acute interventions such as the donning of compression tights, it is questionable to what extent this may influence distance running performance. Whether this improvement in RE translates into meaningful performance benefits is equivocal. A limitation of assessing the role of CGs on exercise performance is that it is impossible to blind the participants to the clothing condition. Studies that have investigated the role of compression tights on distance running performance have demonstrated no effect during a 18.6 km trail run [126] or a 5 km time trial in a hot environment [60].

Improved running economy within the reported exercise intensity range (77.7 – 91.5% $\dot{V}O_{2max}$) would be caused by several factors, including altered biomechanical and neuromuscular systems. In particular, previous studies revealed that lower body compression reduced stride length at 10 and 14 $km \cdot h^{-1}$ [160]. Altered stride length may limit intra-individual gait variability in recreationally active runners[184], maintaining a more consistent gait and contribute toward a lower oxygen cost [185,186]. Conversely, reductions in stride length due to CGs were associated with poorer RE in highly trained runners; [94]. Novice runners demonstrate greater variability in gait characteristics and therefore the physical support offered by compression, or the pressure induced stimulation of mechanoreceptors [80] may limit this variability. Furthermore, RE is related to the stiffness of the propulsive leg, with greater stiffness eliciting the best RE [110].While compression stockings were shown to increase leg stiffness during flat and hilly trail running [84], they elicited no change during submaximal treadmill running [94]. Despite these findings, the influence of compression tights on running leg stiffness is yet to be investigated and may shed light on the observed improvement in RE. Surface EMG studies report lower activation of leg musculature during sub-max running with compression stockings [114] and long tights [153]. Attenuated muscle oscillation may lead to a reduction in recruitment of motor

units [74]. Additionally, the semitendinosus muscle is involved in decelerating the momentum of the swing limb as the knee extends during the mid and late swing phase. Reduced activation of the semitendinosus muscle with compression tights [153] during submaximal running may also be associated with an altered stride length, however this remains to be explored.

5.6.1 Limitations

There are several limitations to this study design that require consideration. The absence of surface electromyography, biomechanical or haemodynamic measures limits the extent in which the observed results can be interpreted. Furthermore, previous studies have reported that the optimal pressure range under resting conditions is 8-18 mmHg of graduated compression across the lower limb. This level of interface pressure is sufficient to significantly increase deep venous velocity and increase venous return[12,98]. The interface pressure applied by the compression tights in the present study is considered low and therefore we are unable to determine the impact of compression tights eliciting a higher interface pressure. Nonetheless, given the present findings, if low interface pressure garments can produce favourable improvements in RE, athletes may opt to choose lower pressure garments given the increased perception of comfort [39].

5.7 Conclusion

This study is the first to identify the influence of compression tights on running economy varies by relative intensity. Wearing compression tights improved running economy at relative exercise intensities above 77.7% $\dot{V}O_{2max}$. Conversely, no effect was observed below this threshold. The mechanism behind these observations requires further investigation to corroborate the plausible explanations presented here.

6 Performance comparison of the MOXY and PortaMon near-infrared spectroscopy muscle oximeters at rest and during exercise

6.1 Rationale

Tissue oxygen saturation is typically measured using near-infrared spectroscopy (NIRS). This non-invasive optical technique reveals *in vivo* muscle oxygenation and haemodynamic status and may provide a mechanistic explanation for the observed improvement in running economy with compression tights. In this investigation, a recently developed low-cost NIRS device (MOXY) was compared against an established PortaMon system that makes use of the spatially resolved spectroscopy (SRS) algorithm, widely used in sports science and physiology research. This is the first study to report the influence of varying external pressure at rest and test-retest reliability at rest and during isometric leg extension exercise of the MOXY device. This study is significant because the use of non-invasive methods to track and optimise training intensity, such as NIRS, is of increasing interest to coaches, athletes and scientists, yet data is lacking regarding the reliability of the MOXY device, nor has its performance been previously compared with alternative NIR systems.

6.2 Abstract

The purpose of the study was to compare muscle oxygenation as measured by two portable, wireless NIRS devices under resting and dynamic conditions. A recently developed low-cost NIRS device (MOXY) was compared against an established PortaMon system that makes use of the spatially resolved spectroscopy (SRS) algorithm. The influence of increasing external pressure on tissue oxygen saturation index (TSI) indicated that both devices are stable between 2 – 20 mmHg. However, above this pressure, MOXY reports declining TSI values. Analysis of adipose tissue thickness (ATT) and TSI shows a significant, non-linear difference between devices at rest. The devices report similar TSI (%) values at a low ATT (<7 mm) (Portamon minus MOXY difference is +1.1 ± 2.8%) with the major subsequent change between the devices occurring between 7 and 10 mm; at ATT values >10 mm the

difference remains constant (-14.7 ± 2.8%). The most likely explanation for this difference is the small source-detector separation (2.5 cm) in the MOXY resulting in lower tissue penetration into muscle in participants with higher ATT. Inter-day test-retest reliability of resting TSI was evaluated on five separate occasions, with the PortaMon reporting a lower coefficient of variation (1.8 - 2.5% vs. 5.7 - 6.2%). In studies on male participants with low ATT, decreases in the TSI were strongly correlated during isometric exercise, arterial occlusion and incremental arm crank exercise. However the MOXY reports a greater dynamic range, particularly during ischemia induced by isometric contraction or occlusion (Δ74.3% vs. Δ43.7%; hyperemia MAX - occlusion MIN). This study shows that in this participant group both MOXY and PortaMon produce physiologically credible TSI measures during rest and exercise. However, the absolute values obtained during exercise are generally not comparable between devices unless corrected by physiological calibration following an arterial occlusion.

Keywords: near-infrared spectroscopy; reliability; muscle oxygen saturation; isometric exercise

6.3 Introduction

The use of wearable devices or wearable bio-sensors, which allow the continuous monitoring of physiological signals, is important for better monitoring of active lifestyles and the diagnosis and treatment of diseases [102]. Near-infrared spectroscopy (NIRS) is a non-invasive technique capable of providing valuable functional insights into skeletal muscle oxidative metabolism *in vivo* during exercise, in healthy and clinical populations. NIRS directly measures the oxygen-dependant absorption of haemoglobin (Hb) in the microcirculation blood vessels (i.e. arterioles, capillaries and venules) and myoglobin (Mb) in the muscle cytoplasm [187].

Dependent on the NIRS device and illumination type, it is possible to retrieve absolute and/or relative concentration values of oxyhaemoglobin (O_2Hb) and deoxyhaemoglobin (HHb), and a derived parameter, total-haemoglobin (tHb = O_2Hb + HHb) [188]. These values are in a large part representative of tissue capillaries, arterioles, and venules because, in larger blood vessels, NIR light is fully absorbed by the high haemoglobin concentration [189]. A further measurement, tissue saturation

index (TSI) represents the ratio of oxygenated (O_2Hb+O_2Mb) concentration to total (tHb+tMb) concentration, reporting on the dynamic balance between O_2 supply and O_2 consumption. Taken as a whole, the range of muscle NIRS parameters can provide information regarding changes in key dynamic physiological indicators, such as blood flow, oxygen extraction and oxygen consumption; muscle NIRS studies are therefore relevant in the evaluation of exercise performance, exercise tolerance [102] and exercise training adaptation that can influence the balance between muscle O_2 delivery and muscle utilization [190].

The use of NIRS as a research tool is well established for studying exercise physiology changes in groups of participants [102,191]. Sports science applications could include monitoring changes in muscle blood flow and oxidative capacity as a function of training [189]. In support of this, positive peripheral muscle oxygenation adaptations have been reported as a consequence of cycling sprint interval training demonstrating that NIRS has the potential to assess the effectiveness of training interventions at the level of the individual athlete [192]. To be effective outside the research laboratory, in an applied exercise environment, there is a requirement for low-cost, portable NIR technology with telemetric capability with the ability to withstand the rigours of sporting environments such as in swimming [193], short track speed skating [194] and trail running [195]

Past studies comparing NIRS monitors have highlighted discrepancies in the values obtained at rest and during exercise in human [196–199] and animal [200] systems. The differences between monitors are likely to be in part associated with the measurement site and spacing of the probes [201,202]. The specific optical properties of the system, whether laser, white light or LED based, as well as the specific NIR wavelengths monitored, could also contribute to differences between systems. These physical properties are most likely reflected in time resolution, signal:noise and reproducibility. However, the absolute numbers of the derived parameters are highly dependent on the algorithms used in the calculations. In terms of measurements of TSI, these methods attempt to remove or correct for the contributions of light scattering and then fit the remaining optical density changes to the known

NIR spectra of the hemo(myo)-globin chromophores. Assumptions are also made about light transport generally assuming the diffusion model.

Time of flight or frequency domain measurements can be used to measure absolute chromophore concentrations, but such devices are currently unlikely to be cheap enough, or portable enough, to be of use for routine physical activity measurements. Manufacturers have therefore focussed on developing methods that only require continuous wave light detection, relying on the use of multi-wavelength or multi-distance analysis to correct for the scattering. Multi-wavelength measures e.g, using second derivative spectroscopy [203,204] are now rarely used. However, the use of multi-distance methods has significantly expanded in recent years. In a recent review, only one of thirteen current devices measured optical density at a single source:detector distance [102].

In general, multi-distance NIR systems correct for light scattering by one of two methods. The most common method used in historical terms is *Spatially Resolved Spectroscopy* (SRS) This measures the slope of the optical density change as a function of multiple distances. Theoretically, the difference in these distances should be small compared to the average source:detector separation. This enables the calculation of scaled absorption coefficient (μ_a) measures which can allow absolute values of chromophore ratios, such as tissue oxygen saturation [205]. The major commercial incarnations of the SRS system historically are the Hamamatsu NIRO and the Artinis OxyMon systems. Alternative Spatial Resolution (SR) methods use a larger separation between measurement sites; light transport models assuming the shorter distance predominantly measures surface tissues and the longer distance deeper tissues, are used to calculate a tissue oxygen saturation for the deeper (muscle/brain) region of interest [206]. The predominant commercial incarnation of this SR method historically is the Medtronic INVOS™ and, more recently the FORE-SIGHT ELITE® and the Nonin EQUANOX™ systems.

Although one can assume that two different devices both using the SRS measurements will generally report similar muscle oxygen saturations, the same cannot be assumed between devices using SR methods given the variety of algorithms in use [207], nor of course between an SRS device and an SR

device. SRS systems have been widely used in exercise physiology and sports science [102,188]. Recently, a new low-cost SR based device, the MOXY monitor, has been marketed to athletes as a training tool to inform the user of exercise intensity [195,208]. The PortaMon, a widely used, portable, SRS oximeter has previously demonstrated a high level of reliability at rest [209] and during isotonic, multi-joint resistance exercise [210]. Conversely, no studies investigating the test-retest reliability of the MOXY device have been conducted.

It would be helpful if users of NIRS devices could be confident that the extensive historical SRS literature on exercise physiology and sports science can be used to help inform their use of this new SR device. The purpose of the study was to compare these two portable, wireless NIRS devices under a variety of resting and dynamic conditions. These conditions include (1) the influence of varying external pressure at rest, (2) test-retest reliability and sensitivity at rest, (3) during isometric leg extension exercise, (4) during dynamic arm-crank exercise and (5) during an arterial occlusion.

6.4 Methods

6.4.1 The NIRS devices

The two NIRS devices used in the assessment of muscle oxygen saturation include the PortaMon (PortaMon, Artinis, Medical System) and MOXY muscle monitor (Fortiori Design LLC, USA).

The PortaMon (Figure 6-1) is a compact (83 x 52 x 20 mm), and lightweight (84 g) NIRS system. It is a dual-wavelength (760 and 850 nm), continuous wave system, containing three pairs of LEDs in a spatially resolved spectroscopy (SRS) configuration with a source-detector spacing of 30, 35, and 40 mm. The device simultaneously uses the modified Beer-Lambert law and SRS methods to calculate the absolute concentration of tissue oxy(+myo)haemoglobin, (O_2Hb), deoxyhemo(+myo)globin (HHb) and total hemo(+myo)globin (tHb). As such, tissue oxygen saturation (TSI) is expressed in % and calculated as $[O_2Hb] / ([O_2Hb] + [HHb]) \times 100$, which is the ratio of HbO_2 to tHb. TSI reflects the dynamic balance between O_2 supply and consumption. During all testing, the system was connected to

a personal computer via Bluetooth™ technology for data acquisition (10Hz), analogue-to-digital conversion and subsequent analysis.

Figure 6-1 *Photograph of the underside (left image) and top (right image) of the PortaMon device (image courtesy of Artinis Medical Systems https://www.artinis.com/portamon)*

The MOXY (Figure 6-2) is a self-contained, compact (61 x 44 x 21 mm), and lightweight (48 g) NIRS system. It employs four wavelengths of NIR light at 680, 720, 760, 800 nm (Schmitz, 2015) and the sensor contains a single light emitting diode (LED) and two detectors placed 12.5 and 25.0 mm from the source. The MOXY device reports a change in total tissue hemo(+myo)globin (tHb) and tissue oxygenation (TSI). During all testing, the system was connected to a personal computer via a commercially available software programme (Peripedal ©) to provide a graphic display of the data. Data acquisition (2Hz) was obtained from the sensors internal memory.

Figure 6-2 *Photograph of the underside (left image) and top (right image) of the MOXY device (image courtesy of MOXY Monitor https://www.moxymonitor.com)*

6.4.2 Testing the Influence of External Pressure

In order to minimize movement artefacts when fixing NIRS devices to the tissue, a variety of supportive bandages or neoprene sleeves are generally used. These sleeves apply external pressure to the device and the surrounding limb area under compression. The influence of external pressure on NIRS derived values is largely undiscussed in the literature, yet if found that TSI data differs due to varying low external pressure this is of importance for both the research and applied user community.

A repeated-measures experimental design was used to determine the influence of external pressure on the reliability of two portable NIRS devices. Four recreationally active male participants ([mean ± SD] age 22.75 ± 5.56 years, body mass 78.03 ± 4.38 kg, height 1.86 ± 0.1 m, vastus lateralis (VL) skinfold thickness 8.30 ± 2.51 mm) volunteered to participate in this study. None of the participants had known health problems or any lower extremity muscle or joint injury. Participants were asked not to perform any strenuous exercise or consume caffeine for at least 24 h prior to visiting the laboratory.

Participants were required to visit the on one occasion. All testing was performed in a controlled laboratory environment (~20 ºC) at the University of Essex Clinical Physiology laboratory. Upon arrival, following the collection of descriptive measures, participants performed 10 min of supine rest on a medical examination bench. The first portable NIRS device was then positioned on the belly of the vastus lateralis, midway between the greater trochanter and the lateral epicondyle of the femur. NIRS devices were placed precisely on the VL, whereby the mid-distance between the closest emitting diode and detector for each device were aligned with the VL location. To ensure the optodes and detector did not move relative to the participants' skin, the device was fixed into position using a waterproof adhesive tape. In addition, bodily hair at or around the sensor placement area was removed from the skin and participants were asked not to moisturise the area on the day of testing. A portable pressure monitor (PicoPress, MircoLabs, Italy) was used to assess the external pressure applied to the leg. An air-filled bladder was placed on the medial aspect of the thigh, at the same vertical alignment to the NIRS device location. A surgical marker pen was used to mark the position of NIRS device and bladder placement in order to identify any movement during testing and ensure the second NIRS

device was placed at the same location [192]. A black neoprene thigh sleeve (Mueller, WI, USA) was wrapped around the leg to secure the NIRS device in place firmly against the skin and also ensure that no external light would be received by the device detectors.

Incremental external pressure (mmHg) was applied to the surrounding area, encompassing the NIRS device and pressure monitor bladder, using an aneroid sphygmomanometer (Welch Allyn Inc., New York, NY, USA) connected to a thigh blood pressure cuff (Accoson Works, Essex, UK). All measurements were recorded in a supine position; with the order of NIRS device application counterbalanced. Initial external pressure applied was 2 mmHg as a result of the neoprene strapping, prior to inflating a blood pressure cuff in a step-wise manner.

Initially, the investigator visually observed the live NIRS data on a personal computer until a stable value was achieved and collected 60 s of data. Stability was defined as a TSI variation <2% over 30 seconds [211]. This procedure was repeated for all NIRS devices. After 4 min of baseline data collection with the neoprene strap applying 2 mmHg, the sphygmomanometer was inflated to elicit a pressure of 5 mmHg, with 5 mmHg increments every 4 minutes thereafter, up to and including 30 mmHg. The data acquired from the PortaMon system was downsampled from 10 Hz to 2 Hz to allow for comparison with the MOXY system. Values are reported as average absolute TSI, calculated from the final 60 seconds of each 4 min period. Descriptive statistics are presented as mean (TSI) unless otherwise stated. A simple linear regression was then used to calculate slopes of the NIRS device vs. external pressure. Subsequently, the TSI of PortaMon minus MOXY at incremental external pressures could be fitted by a sigmoid curve. All analyses were performed using Graphpad Prism 7 (Graphpad Software, San Diego, CA).

6.4.3 Comparing Devices at Rest

Muscle oxygenation of the dominant vastus lateralis muscle of each participant was measured with two MOXY ($MOXY^1$ and $MOXY^2$) and two PortaMon ($PortaMon^1$ and $PortaMon^2$) devices to assess between and within-device variation. Twenty-one male ([mean ± SD] age 22.33 ± 4.84 years, body mass 78.24 ± 10.62 kg, height 1.79 ± 0.1 m, VL skinfold thickness 11.59 ± 5.09 mm) and nine female

participants (age 21.67 ± 2.40 years, body mass 65.14 ± 7.44 kg, height 1.69 ± 0.04 m, VL skinfold thickness 26.36 ± 4.77 mm) volunteered to participate in this study. The experimental protocol involved a single visit to the laboratory. Upon arrival, participants performed 10 min of supine rest on a medical examination bench. The first of four NIRS devices were positioned on the vastus lateralis muscle (as described in Sec 2.2) and all measurements were recorded in a supine position. Using a portable pressure monitor, care was taken to ensure the same external pressure (~8 mmHg) was exerted by the neoprene strapping surrounding the NIRS device, during each condition. Device order was counterbalanced using a Latin square design. The investigator visually observed the live NIRS data on a personal computer until a stable value was achieved (minimum 2 min) and collected 60 s of data. This procedure was repeated for all four NIRS devices.

Descriptive statistics are presented as mean ± SD unless otherwise stated. A one-way analysis of variance (ANOVA) was used to compare mean values of resting TSI between the four NIRS devices. A Tukey's range test was used for *post hoc* multiple comparisons. Subsequently, an unpaired t-test was performed to compare the combined average of two similar devices at rest (Mean TSI (PortaMon + PortaMon) vs. Mean TSI (MOXY + MOXY). Accuracy was calculated as the mean absolute difference, using Bland-Altman agreement plots (±2SD) between resting TSI. A 95% confidence interval of the mean (95%CL) is also presented for each case. The difference between devices was calculated as the mean TSI of PortaMon minus MOXY. A Pearson's product-moment correlation analysis was used to compare the association between resting values of TSI and quadriceps skinfold thickness (adipose tissue thickness (ATT) = 0.5 x mean skinfold thickness). Significance was set at $P < 0.05$. All statistical analyses were performed using Graphpad Prism 7 (Graphpad Software, San Diego, CA).

6.4.4 Test – Retest Reliability and Sensitivity of Devices at Rest

Five male participants ([mean ± SD] age 21.2 ± 2.7 years, body mass 71.5 ± 7.7 kg, height 1.78 ± 0.1 m, VL skinfold thickness 11.3 ± 5.3 mm) completed repeated resting measures assessing vastus lateralis TSI (%) for a total of five occasions. Each visit to the laboratory was separated by at least 24

hours, thereby providing a method of assessing inter-day test – retest reliability of four NIRS devices (MOXY[1], MOXY[2], PortaMon[1] and PortaMon[2]). Upon arrival on each occasion, participant's vastus lateralis was identified as described in Sec 2.2. Neoprene strapping was carefully tightened around the NIRS device to ensure a pressure of 8 mmHg was exerted. The same researcher attached each device on every occasion to minimise inter-tester variability. After 10 minutes supine rest, the investigator visually observed the live NIRS data on a personal computer until a stable value was achieved (minimum 2 min) and collected 60 s of data. This procedure was repeated for all four NIRS devices using a Latin square design.

Descriptive statistics are presented as mean ± SD unless otherwise stated. The mean participant TSI for each NIRS device was used as an indicator of test-retest reliability [157]. The coefficient of variation (CV) was calculated as a characteristic of the performance of within-participant evaluation [212], with a CV below 5-10% considered as acceptable absolute reliability [210].

All statistical analyses were performed using Microsoft Excel and GraphPad Prism 7.

6.4.5 Comparing Devices during Isometric Exercise

A repeated isometric quadriceps contraction exercise protocol was implemented to compare the delta (Δ) TSI between four NIRS devices (MOXY[1], MOXY[2], PortaMon[1] and PortaMon[2]). The same five male participants ([mean ± SD] age 21.2 ± 2.7 years, body mass 71.5 ± 7.7 kg, height 1.78 ± 0.1 m, VL skinfold thickness 11.3 ± 5.3 mm) who underwent the test-retest reliability assessment at rest (see Sec 6.3.4), participated in a quadriceps isometric contraction task. Participants were asked not to perform any strenuous exercise or consume caffeine for at least 24 h prior to visiting the laboratory.

During the initial visit, the participant's maximal voluntary isometric contraction (MCV) was determined. Prior to the isometric contraction task, a nonspecific warm-up on a cycle ergometer (Monark, 824E) was completed, before performing a maximal voluntary isometric contraction (MVC) of the knee extensors using an isokinetic dynamometer (KinCom, Chattanooga Inc., TN, USA). Participants were positioned upright on the dynamometer ensuring the knee joint (lateral femoral

epicondyle) and dynamometer axes were accurately aligned and stabilised using leg, waist, and chest straps to minimise trunk movement during testing. The seat height and distance from the axis was recorded to ensure accurate repeat positioning. The dominant leg was then fixed at a 60º angle and three submaximal repetitions of a 5 s continuous quadriceps isometric contraction were performed. Participants then performed 3 maximal contractions interspersed with a 60 s rest period. The best of the three contractions was considered the maximal isometric force and values for 30% and 50% MVC were then calculated.

During the second visit, after resting data was collected from all four NIRS devices (see Sec 6.3.3), the final NIRS device was left attached to the participant's leg for the duration of the quadriceps isometric contraction task. Participants were positioned on the dynamometer (as described above) with no warm-up. After a stable pre-test TSI value was attained, the participants were instructed to perform two 30 s sustained isometric quadriceps contractions to the previously defined values of their MVC (30% and 50%) interspersed by a 3 min rest period. TSI was continuously monitored throughout the procedure. This procedure was repeated for visits 3, 4, and 5 using a different NIRS device during the isometric contraction task.

Due to potential differences in resting values for the two devices (Sec. 6.3.3, 6.3.4), TSI was reported as a change from pre-test (60 s averaging before each test). Maximum and minimum TSI values were calculated as a three-second average surrounding the highest and lowest values during each of the two isometric contractions. The Δ in TSI was calculated as the maximum value minus the minimum value during each 30 s contraction e.g. TSI Max—TSI Min = ΔTSI [193].

Descriptive statistics are presented as mean ± SD unless otherwise stated. A one-way analysis of variance (ANOVA) was used to compare mean values of ΔTSI between the four NIRS devices. A Tukey's range test was used for *post hoc* multiple comparisons. Accuracy was calculated as the mean absolute difference, using Bland-Altman agreement plots (±2SD) between resting TSI. A 95% confidence interval of the mean (95%CI) is also presented for each case. The difference between devices was calculated as the mean TSI of MOXY minus PortaMon. All statistical analyses were

performed using Graphpad Prism 7 (Graphpad Software, San Diego, CA). The studies undertaken all received ethical approval from the University of Essex ethical committee and participants provided written informed consent before inclusion.

6.4.6 Comparing Devices during Dynamic Exercise and Occlusion

An incremental asynchronous arm crank exercise protocol, followed by a 5 minute arterial occlusion, was undertaken to compare TSI values between two NIRS devices (MOXY[1] vs PortaMon[1]). Based on the effect size observed between NIRS devices during isometric exercise at 50% MVC, a power analysis for a dependant sample t-test was conducted using G*Power to determine a sufficient sample size using an alpha of 0.05, a power of 0.80, a large effect size (d = 2.9) and two tails [213]. Based on the aforementioned assumptions, the desired sample size is 4. We elected to recruit an additional two participants to allow for participants terminating the arterial occlusion early due to the sensation of pain. Six male participants ([mean ± SD] age 23.7 ± 4.1 years, body mass 73.3 ± 5.2 kg, ATT 2.7 ± 1.0 mm) completed the exercise and occlusion task, requiring two separate visits to the laboratory, separated by 3 -7 days. On arrival, following basic anthropometrical measures, the participant confirmed their dominant arm (all participants' self-reported right hand dominance) and adipose tissue thickness was assessed at the muscle belly of the biceps brachii, 8 cm above the mid-arm fold. The first NIRS device was positioned on the biceps brachii, where the 8 cm marker was used to determine the mid-point between the device emitter and detectors. The biceps brachii were chosen as previous literature has reported this muscle eliciting the greatest decrease in tissue oxygenation index during arm cranking compared with the triceps brachii, brachioradialis and anterior deltoid [190]. A portable pressure monitor was used to ensure a similar external pressure was exerted by the black crepe bandage used to hold the device in place. Subsequently the participant's sat upright, with hands in a rested position until a stable TSI value was achieved (minimum 2 min) and a resting baseline was obtained over a 5 minute period.

Prior to arm cranking, participants were positioned with the crank axis aligned to shoulder height, at a distance that allowed a slight bend in the elbow when arms were extended. A chest strap was applied

to minimise trunk movement during testing and seat/crank height were recorded to ensure accurate repeat testing. Participants were required to arm-crank at 60 rpm beginning at 0 Watts (W) and increasing by 25 W every 2 min. The exercise end-point was determined when cadence fell below 60 rpm for 3 consecutive seconds.

Following completion of the incremental arm-crank exercise task, participants remained seated with hands in a rested position for 5 min prior to an arterial occlusion. To enable a physiological calibration of raw TSI values by identifying the participant's notional minimum and maximum TSI, an arterial occlusion was applied for 5 minutes using an automated pneumatic cuff inflator (Hokanson, Bellevue, USA) positioned at the proximal aspect of the humerus, applying 295-305 mmHg of pressure. After a 5 min occlusion, the cuff was released and participant's continued to rest for a further 5 min period. This procedure was repeated for the second visit using the alternative NIRS device. Although we cannot be sure that this value exactly corresponds to complete deoxygenation of haemoglobin and myoglobin, in all participants this time was sufficient to result in a stable minimum in saturation value significantly lower than any observed during exercise.

Initially, the data acquired from the PortaMon system was down sampled from 10 Hz to 2 Hz to match that of the MOXY system. Following this, both device data-sets were smoothed by calculating the 3 second moving average at 2 Hz. To normalize the NIRS signal and achieve a physiological calibration, the average value of the final 30 seconds was used to determine notional 0% oxygenation (calibration) and the 30 second peak hyperemic response upon release of the cuff was used to indicate notional 100% oxygenation (we use the term "notional" as we cannot be absolutely sure that the lower value could not be decreased further by adding an ischemic exercise component, not that the upper value could not be increased by hyperoxia and/or methods to increase blood flow or decrease oxygen consumption; however, the current physiological calibration has the advantage of being relatively easy to implement and in common use in the field). The Δ in TSI during the occlusion task was calculated as the maximum value minus the minimum value, identified from the onset of the cuff inflating to the period following the hyperemic response upon cuff release.

During the incremental test, TSI was established for each power output as the final 30 second average for each stage. These values were subtracted from the resting baseline TSI to provide a delta (Δ) raw TSI and subsequently converted to a calibrated (% calibration) value.

Descriptive statistics are presented as mean [95% CI] unless otherwise stated. Paired *t*-tests were used to compare performance outcomes of the arm-crank test and compare device minimum, maximum and delta values for raw (TSI) and calibrated (% calibration) data during the occlusion. Furthermore, a repeated measure ANOVA was conducted to compare values obtained during the incremental arm-crank test for each power output. Significant F ratios were examined on a *post hoc* basis using an uncorrected Fisher's LSD test. Where data was not obtained for all participants at peak power output (i.e. only three participants completed the 100 W stage), a paired t-test was conducted on the smaller sample size to compare differences between devices. The incremental data is reported as the change from resting baseline in both raw (ΔTSI) and calibrated units (Δ calibration %). A simple linear regression was then used to calculate slopes of the NIRS device vs. power output.

6.5 Results

6.5.1 Testing the Influence of External Pressure

There was a significant correlation between TSI and external pressure for both MOXY and PortaMon devices (Fig. 6-3a), in both cases showing a drop in TSI with increasing pressure. The slope was significantly steeper for the MOXY than the Portamon (a slope of -0.38 ± 0.09 % TSI per mmHg for the MOXY compared to -0.08 ± 0.03 for the PortaMon). The PortaMon reports a lower resting TSI (%) at low pressure (<20mmHg); with the major subsequent change between the devices occurring between 20 and 30 mmHg (Fig. 6-3b). Therefore to decrease variability the subsequent studies were all undertaken at lower than < 20mmHg, with a target external pressure of 8 mmHg when participants were supine.

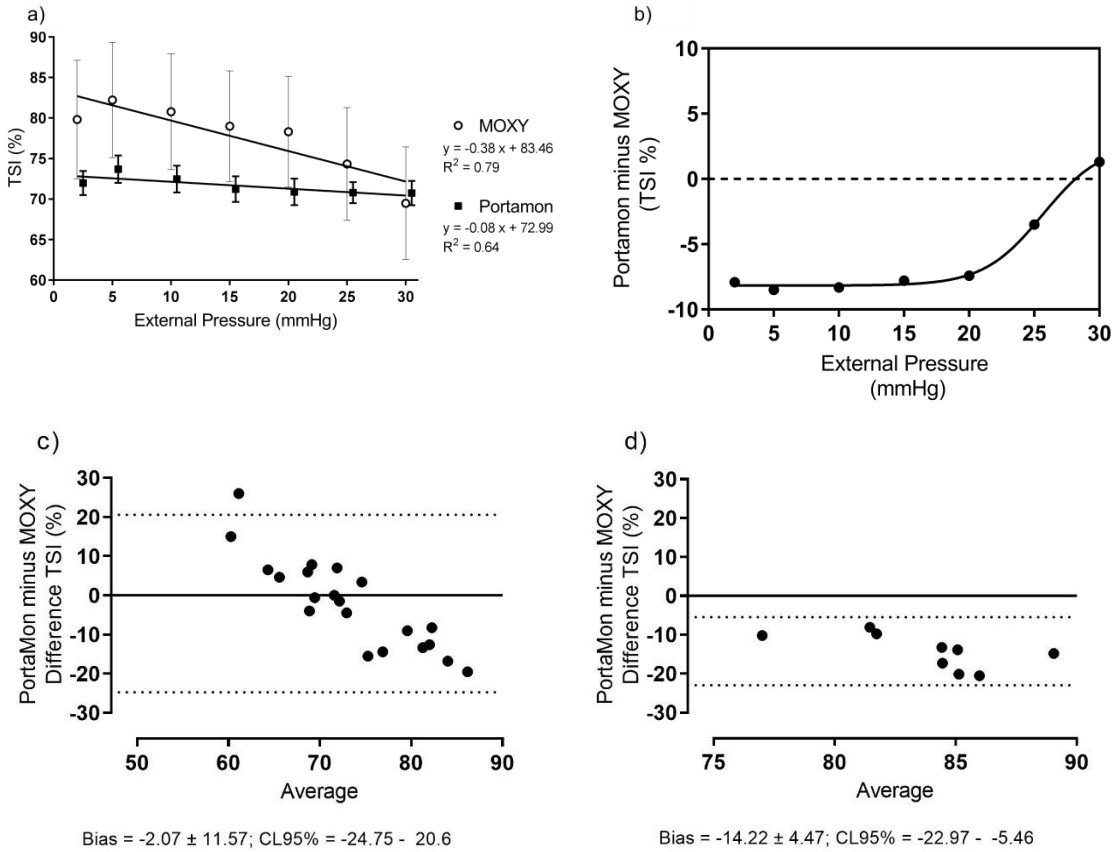


Figure 6-3 (a) *Linear regression showing TSI as a function of external pressure (mmHg) (mean ± SEM),* ***(b)*** *PortaMon minus MOXY (TSI) as a function of external pressure (mmHg). Data fit using non-linear regression to a sigmoidal curve for illustrative purposes and* ***(c)*** *Bland-Altman plots of resting TSI of males (n = 21) and* ***(d)*** *females (n = 9) using the combined average of MOXY and PortaMon devices. Each plot represents the difference versus the average of the two devices. Dotted lines represent the ±2SD limits of agreement*

6.5.2 Comparing Devices at Rest

Resting TSI of male and female participants for four NIRS devices is provided in Table 6-1. A one-way ANOVA of mean resting TSI between the four NIRS devices for female participants demonstrated a significant difference ($P < 0.05$), with posthoc multiple comparisons showing a significant difference between MOXY and PortaMon devices (MOXY[1] vs. PortaMon[1]; MOXY[1] vs.

PortaMon^2; MOXY^2 vs. PortaMon^1; MOXY^2 vs. PortaMon^2 = $P < 0.05$). Conversely, no difference was found between devices for male participants.

Table 6-1 Male and female mean TSI of four NIRS devices at rest.

	Male TSI (%)	Female TSI (%)
	Mean ± SD [95% CI]	Mean ± SD [95% CI]
MOXY^1	75.2 ± 13.1 [69.3, 81.2]	92.7 ± 5.0 * [88.8, 96.6]
MOXY^2	73.3 ± 12.8 [67.5, 79.2]	89.1 ± 6.3 * [84.3, 94.0]
PortaMon^1	72.8 ± 3.5 [71.2, 74.4]	77.3 ± 2.7 [75.2, 79.4]
PortaMon^2	71.6 ± 3.7 [70.0, 73.3]	76.1 ± 2.8 [74.0, 78.3]
Combined MOXY	74.3 ± 12.8 [68.5, 80.1]	90.9 ± 5.1** [87.0, 94.9]
Combined PortaMon	72.2 ± 3.5 [70.6, 73.8]	76.7 ± 2.6 [74.7, 78.7]

* Significantly different from PortaMon^1 and PortaMon^2 ($P > 0.05$);

** Significantly different to Combined PortaMon ($P > 0.001$)

As no significant difference was found at rest between either MOXY^1 vs. MOXY^2 or PortaMon^1 vs. PortaMon^2, the combined mean TSI for MOXY (MOXY^1 & MOXY^2) and PortaMon (PortaMon^1 & PortaMon^2) at rest for male and female participants (Table 6-1) was compared using an unpaired t-test. Mean female MOXY TSI (90.9 ± 5.1 %) was significantly higher than the PortaMon (76.7 ± 2.6 %) ($t(16) = 7.4$, $P < 0.05$), however no significant difference was observed in male participants between the MOXY (74.3 ± 12.8 %) and PortaMon (72.2 ± 3.5 %) devices.

At rest, Bland-Altman plots of male participants (Fig. 6-3c) suggest the MOXY device reports a higher saturation value at higher resting TSI and a lower value at lower resting TSI. So the lack of a significant difference of the mean value masks a real measurement difference between the devices even in male participants. Bland-Altman plots of resting female participants (Fig. 6-3d) illustrate a

consistently higher TSI with the MOXY device vs PortaMon, regardless of average TSI, consistent with the difference in the mean values.

Vastus lateralis skinfold thickness (mm) and resting TSI (%) are highly correlated using the combined mean TSI MOXY (r =.70, $P < 0.01$) and PortaMon device (r =.73, $P < 0.01$). Linear regression of VL skinfold thickness and TSI (Fig. 6-4) show the difference between the slopes (MOXY vs PortaMon) are significantly different ($F(1,54) = 11.97$, $P = 0.001$). The MOXY device shows a regression slope ($y = 1.12*x + 61.22$), steeper than that of the PortaMon ($y = 0.34*x + 68.16$). This indicates that as skinfold thickness increases, the rise in TSI is greater with the MOXY. The difference between the two values is non-linear with respect to ATT (Fig. 6-5). The PortaMon and MOXY devices report similar TSI (%) values at a low ATT (<7 mm); with the major subsequent change between the devices occurring between 7 and 10 mm; at ATT values >10 mm the difference remains constant. The data fit well to a sigmoidal dose-response relationship. At the lowest ATT the (Portamon minus MOXY) difference is +1.1 ± 2.8%; (Mean + SEM), at the highest ATT the difference is -14.7 ± 2.8%; the 50% change occurs at 8.5 ± 0.6 mm ATT.

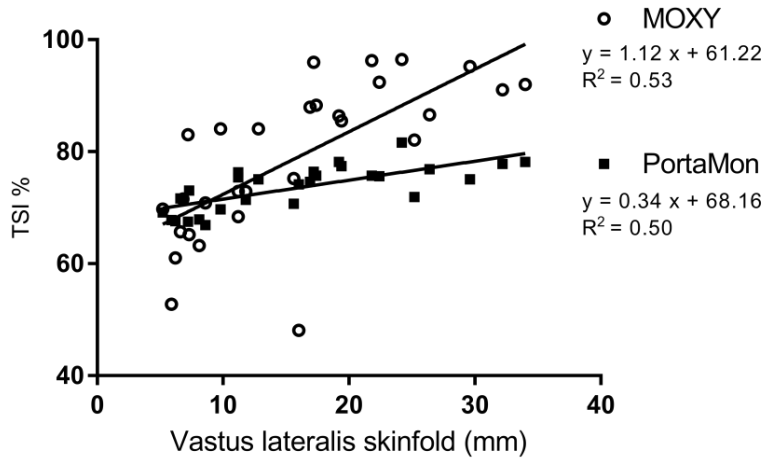


Figure 6-4 *Relationship between mean TSI and vastus lateralis skinfold (mm) using the combined average of MOXY and PortaMon devices*

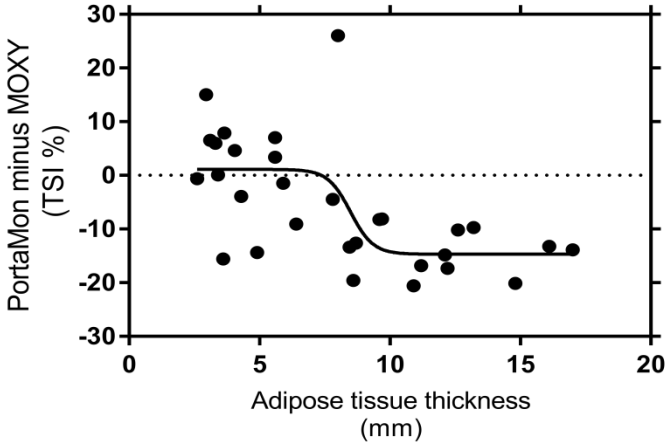


Figure 6-5 *PortaMon minus MOXY (TSI) as a function of adipose tissue thickness (mm). Data fit using non-linear regression to a sigmoid dose-response curve.*

6.5.3 Test – Retest Reliability of Devices at Rest

The CV for all NIRS devices are listed in Table 6-2. The mean CV values were lower for the Portamon (<2.5%) when compared with the MOXY devices (5.7 – 6.2%), however, both devices were below the acceptable threshold of 10%. The SD of the individual devices highlights a smaller measurement variation when using the PortaMon, suggesting that the inter-individual variation across repeated measures is less than the MOXY device.

Table 6-2 Test-retest measures of device reliability (TSI) at rest.

	MOXY[1]		MOXY[2]		PortaMon[1]		PortaMon[2]	
Participant number	Mean ± SD	CV (%)	Mean ± SD	CV (%)	Mean ± SD	CV (%)	Mean ± SD	CV (%)
1	52.9 ± 4.4	8.4	52.7 ± 3.5	6.7	67.9 ± 1.0	1.5	66.6 ± 1.2	1.7
2	87.8 ± 4.8	5.4	82.9 ± 4.9	5.9	74.7 ± 1.9	2.5	73.8 ± 1.3	1.8
3	56.9 ± 5.5	9.6	53.7 ± 4.9	9.2	66.0 ± 1.1	1.7	64.7 ± 2.6	4.1
4	87.2 ± 3.1	3.6	84.9 ± 3.3	3.9	71.3 ± 0.8	1.1	70.0 ± 1.6	2.3
5	71.8 ± 2.7	3.8	70.1 ± 1.9	2.7	72.7 ± 1.6	2.2	71.1 ± 1.8	2.6
Grouped Data								
CV (%)	6.2 [2.8, 9.5]		5.7 [2.5, 8.8]		1.8 [1.1, 2.5]		2.5 [1.3, 3.7]	

CV, coefficient of variation [95% confidence interval];

6.5.4 Comparing Devices during Isometric Exercise

Mean torque of 30 and 50% MVC was 256.9 ± 43.5 and 428.2 ± 72.5N respectively. A one-way ANOVA of ΔTSI during 30 and 50% MVC between the four NIRS devices demonstrated a significant difference ($P < 0.05$), with posthoc multiple comparisons showing a significant difference between MOXY and PortaMon devices (MOXY[1] vs. PortaMon[1]; MOXY[1] vs. PortaMon[2]; MOXY[2] vs. PortaMon[1]; MOXY[2] vs. PortaMon[2] = $P < 0.05$). Table 6-3 displays the ΔTSI values.

Table 6-3. Δ change in TSI (%) values during 30 s quadriceps isometric contraction task at 30% and 50% maximal voluntary contraction (MVC) of each NIRS device Mean ± SD (range).

	MOXY[1]	MOXY[2]	PortaMon[1]	PortaMon[2]
ΔTSI 30% MVC (%)	36.5 ± 7.3 [a] (28.4 – 47.7)	37.9 ± 14.4 [a] (15.2 – 55.2)	9.4 ± 4.4 (5.0 – 16.3)	8.3 ± 4.8 (2.9 – 15.7)
ΔTSI 50% MVC (%)	57.3 ± 14.9 [b] (41.3 – 77.2)	60.8 ± 13.7 [b] (42.3 – 75.9)	14.2 ± 2.3 (11.7 – 16.7)	14.8 ± 4.3 (9.9 – 19.7)

[a] = significant difference from PortaMon[1] and PortaMon[2] at 30% MVC ($P > 0.05$); [b] = significant difference from PortaMon[1] and PortaMon[2] at 50% MVC ($P > 0.05$).

No significant difference was found during the isometric quadriceps exercise between either MOXY[1] and MOXY[2] or PortaMon[1] and PortaMon[2]. As such, the combined group averaged data (n = 5) for MOXY (MOXY[1] & MOXY[2]) and PortaMon (PortaMon[1] & PortaMon[2]) during the quadriceps isometric contraction task is shown as a composite graph in Figure 6-6a. The general trend was similar for all five participants between devices. For both systems, an immediate decrease in TSI at the onset of isometric contraction (30% MVC) was observed. This recovered rapidly following contraction cessation, and in some cases overshooting (a hyperaemic response). A larger decrease in TSI was observed at 50% MVC and returning to resting at task cessation. Bland-Altman plots indicate that the MOXY reports consistently higher ΔTSI at both 30 (Fig. 6-6b) and 50% (Fig. 6-6c) MVC, with a trend showing the greater the average ΔTSI, the greater the difference.

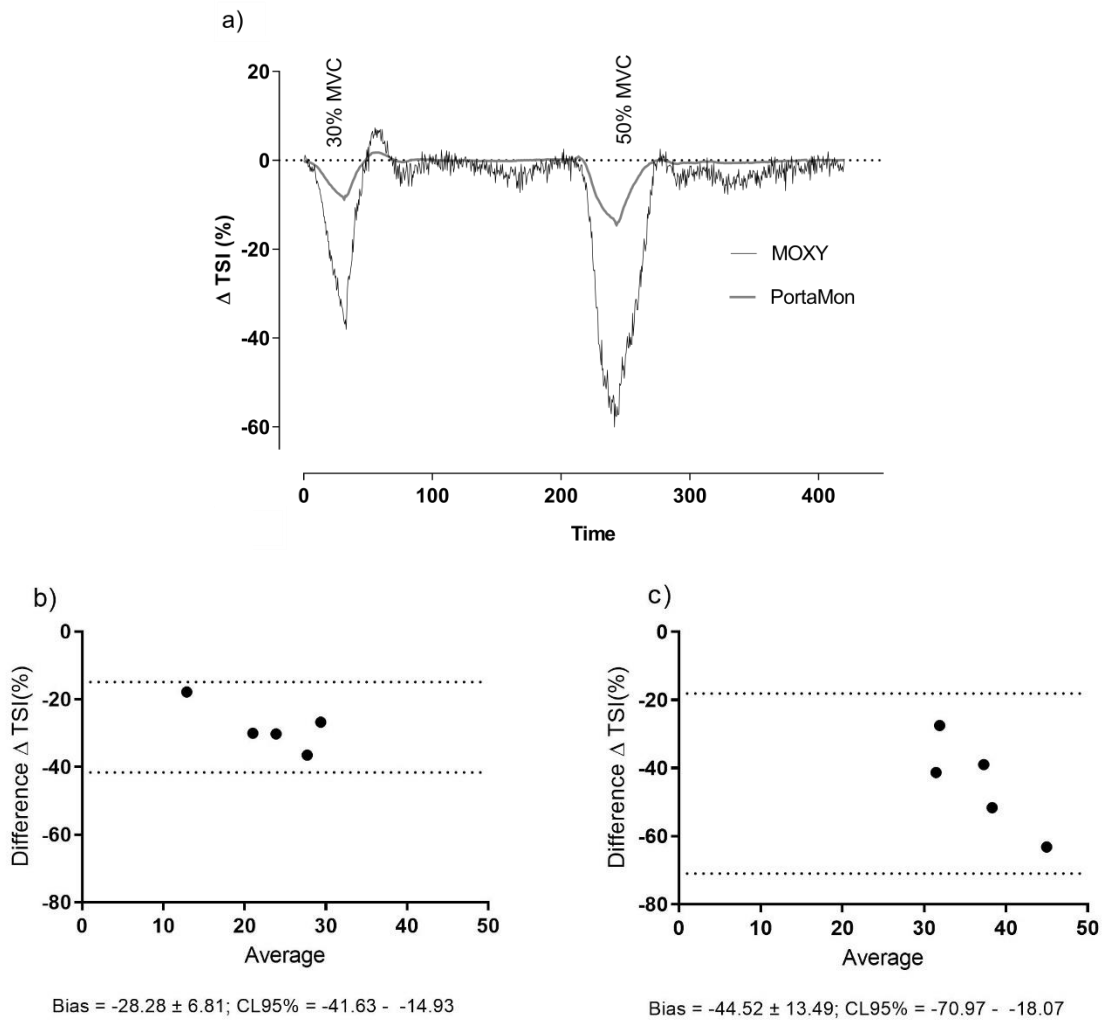


Figure 6-6 (a) *Group changes in tissue saturation index (ΔTSI) during 30 and 50% isometric MVC tasks and* ***(b)*** *Bland-Altman plots of ΔTSI at 30% MVC (n = 5) and* ***(c)*** *50% MVC (n = 5) using the combined average of MOXY and PortaMon devices. Each plot represents the difference versus mean Δ value measured as the average of the two MOXY devices compared to the two PortaMon devices. Dotted lines represent the ±2SD limits of agreement.*

6.5.5 Comparing devices during dynamic exercise and occlusion

Peak performance measures, adipose tissue thickness, external pressure applied by the NIRS devices and TSI data during the incremental arm crank test and subsequent arterial occlusion are presented in Table 6-4. No significant differences were observed for peak power output or time to exhaustion between trials and external pressure was applied between 9 – 13 mmHg. During the arterial occlusion

and the following reactive hyperaemia, significant differences were observed between NIRS devices for minimum, maximum and delta TSI. The MOXY device repeatedly reported a greater delta TSI when compared with the PortaMon (p <0.01).

During the incremental arm crank test, between-device TSI differences were observed at 25 W when comparing raw TSI values. In the post-exercise hyperaemic period, the MOXY device also reported a significantly greater maximum value compared with the PortaMon (p <0.01). However, these differences were not observed when the TSI range of the devices was calibrated to the min and max TSI associated with the arterial occlusion.

Despite the lack of significant differences seen at individual power values using the calibrated values, when the data is taken as a whole, a subtle distinction can be observed. Figure 6-7 demonstrates the relationship between increasing power output and a progressive decrement in TSI. The regression slope was not significantly different (P = 0.18) between the MOXY and the PortaMon device for the raw TSI values (Fig. 6-7a) (a slope of -0.16 ± 0.02 % TSI per 1W for the MOXY compared to -0.12 ± 0.005 for the PortaMon), however the lines are not identical due to a significant difference in the intercepts ($F(1,7) = 47.06$, P = <0.01. A similar result is present when comparing the regression slopes of the calibrated values (Fig. 6-7b) between devices (P = 0.45), reporting similar decrements in TSI (% calibrated) per 1W increase (MOXY = -0.23 ± 0.03 %; PortaMon = -0.26 ± 0.006 %), yet a statistically significant difference in the intercepts ($F(1,7) = 12.95$, P = <0.01). The difference in the intercepts appears to be due to a lower value of the MOXY after warm up compared to baseline (the 0W point is arm cranking with zero resistance compared to complete rest).

Figure 6-8 shows the raw and calibrated TSI traces during incremental arm cranking and the subsequent arterial occlusion for individual participants. It is evident from these figures that both devices follow a similar trend within individuals between both MOXY and PortaMon devices. Interestingly, following a rapid desaturation during the initial two stages of the arm crank test (0 and 25 W), the TSI trace for participant 3 increased from 50 W to the end of the test. This physiological observation was reproduced by both devices for this individual on separate testing occasions.

Table 6-4 Physiological responses during arm cranking and subsequent arterial occlusion.

	MOXY		PortaMon		*P*-value
ATT (mm)	2.7 [1.6, 3.7]				
External pressure (mmHg)	10.8	[8.7, 13.0]	11.5	[9.5, 13.5]	0.60
TTE (s)	589.7	[538.1, 641.3]	584.7	[515.5, 653.8]	0.64
PPO (W)	97.85	[87.1, 108.6]	96.81	[82.4, 111.2]	0.64
Arterial Occlusion					
Min (TSI)	12.9	[7.7, 17.9]	36.6	[28.7, 44.4]	<0.01 **
Max (TSI)	87.2	[85.3, 89.0]	80.2	[77.4, 83.0]	<0.01 **
Delta (TSI)	74.3	[68.9, 79.8]	43.7	[37.7, 49.7]	<0.01 **
Baseline (resting)					
Raw (TSI)	61.5	[54.1, 68.9]	64.4	[60.9, 67.9]	0.34
Calibrated (%)	66.5	[55.0, 77.9]	63.6	[54.2, 73.0]	0.43
Incremental Test					
Raw (Δ from baseline)					
0W	-2.1	[-7.6, 3.5]	0.2	[-4.0, 5.4]	0.50
25W	-9.6	[-14.4, -4.8]	-2.5	[-4.8, 9.3]	0.04 *
50W	-11.1	[-16.5, -5.7]	-5.6	[-10.4, 7.9]	0.12
75W	-14.3	[-22.8,-5.8]	-8.3	[-16.2, 7.1]	0.09
100W *(n = 3)*	-19.1	[-25.8, -12.5]	-12.3	[-23.8, -0.8]	0.22
Calibrated (Δ from baseline)					
0W	-4.2	[-11.8, 3.5]	-0.3	[-14.6, 14.0]	0.55
25W	-14.3	[-21.7, -7.0]	-6.9	[-24.5, 10.7]	0.27
50W	-16.0	[-25.0, -7.0]	-13.9	[-26.2, -1.5]	0.74
75W	-20.9	[-34.1, -7.6]	-19.1	[-31.5, -6.7]	0.80
100W *(n = 3)*	-29.7	[-44.2, -15.3]	-25.8	[-44.4, -7.3]	0.59
Post Ex. *Hyperemic Max:*					
Raw	85.5	[80.4, 90.5]	80.7	[75.6, 85.9]	<0.01 **
Calibrated	97.8	[93.0, 102.6]	101.3	[92.7, 109.8]	0.12

* $P = < 0.05$; ** $P = < 0.01$;

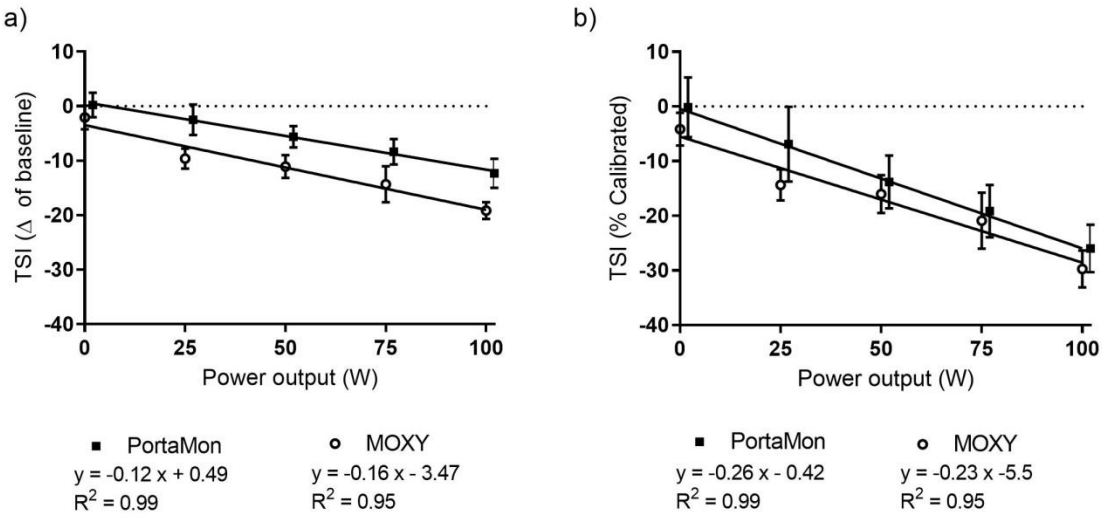


Figure 6-7 (a) *Relationship between power output and raw Δ TSI and* ***(b)*** *calibrated (%) values during incremental arm cranking (mean ± SEM)*

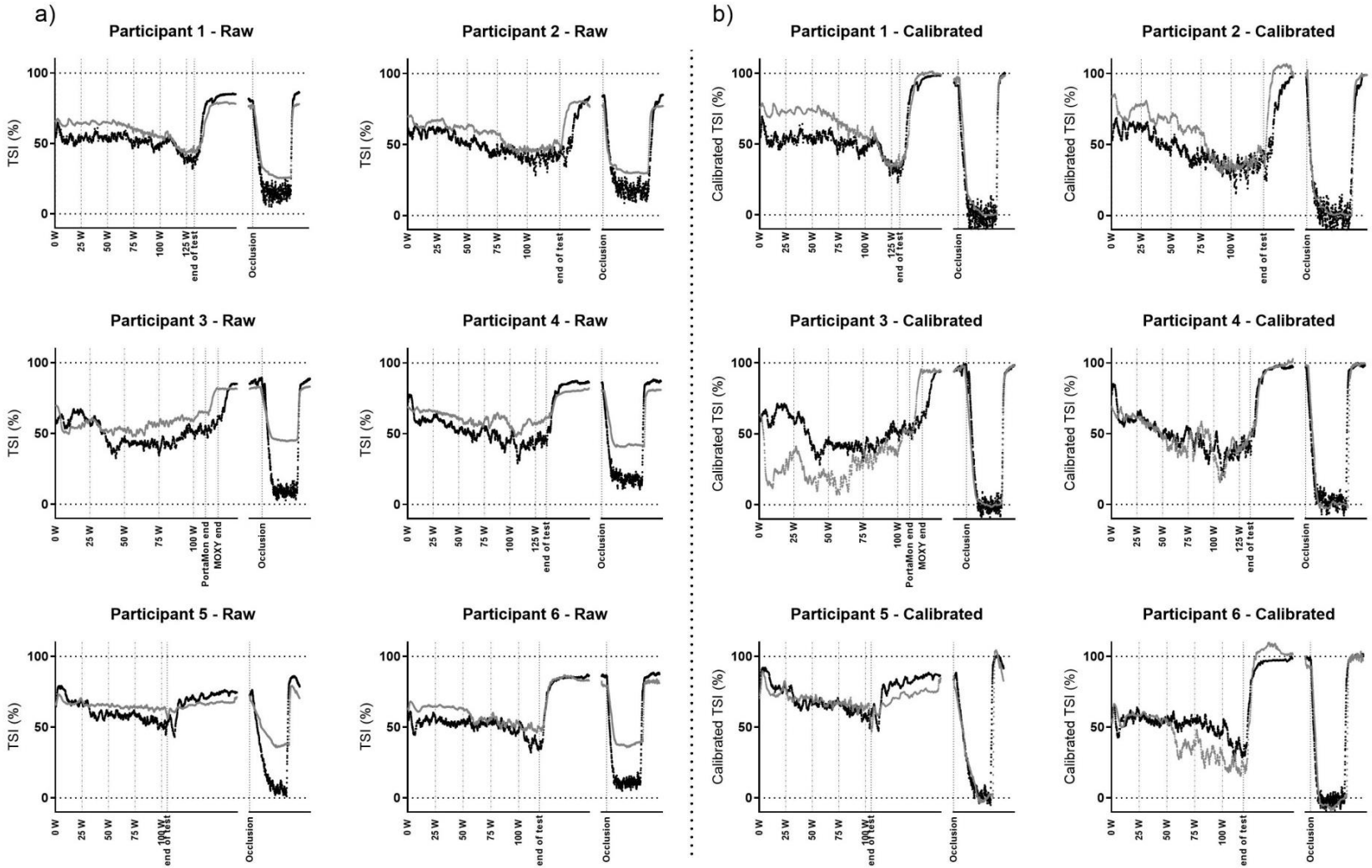


Figure 6-8 (a) *Individual participant TSI traces for raw and* ***(b)*** *calibrated values during arm cranking and arterial occlusion (MOXY = black line; PortaMon = grey line).*

6.6 Discussion

This current study compared two portable, wireless NIRS devices. Whilst the measurement of muscle oxygen saturation correlated between the MOXY and PortaMon under a variety of resting and dynamic conditions, significant differences were noted, both with respect to device reliability and absolute values of saturation.

6.6.1 Comparing Devices at Rest

Light entering the surface above the vastus lateralis will pass through skin and adipose tissue layers before entering the muscle. It is generally assumed that NIR light reaching a detector has an effective penetration depth of approximately 50 – 60% of the inter-optode distance [214]. The PortaMon (maximum source:detector separation of 40mm) would be expected to detect more light from the deeper muscle tissue than the MOXY (maximum source:detector separation of 25mm). Even in the absence of differences in the measurement algorithm (discussed later), one would therefore not necessarily expect identical muscle oxygen saturation values for the two systems.

Whilst the two devices did provide similar values for male participants, in female participants, the PortaMon reported a lower resting TSI when compared with the MOXY. We showed that this difference appeared to be consequent to the gender difference in adipose layer. Optical density is greater in participants with a thin layer of adipose tissue [215]. In SRS systems the increased adipose layer results in a higher apparent %TSI in female participants [216]. This effect is exaggerated in the MOXY. The smaller source:detector separation in the MOXY biases the light detected in favour of more surface tissues. It seems that the SR algorithm used is unable to completely correct for this effect. It is therefore even more important than usual in NIRS to measure and report on local body fat composition when using the MOXY, especially when comparing between participants.

6.6.2 Testing the Influence of External Pressure

There were significant effects of the applied pressure on resting TSI, especially for the MOXY. At low external pressures (2 – 20 mmHg), the PortaMon reported a lower resting TSI (~8%) compared with

the MOXY. As external pressure was increased above 20 mmHg, the difference between the two devices diminished. This difference was predominantly due to changes in the MOXY value, not the PortaMon. In particular, MOXY values showed a sharp decrease between 20 and 30 mmHg. As external pressure is applied to the skins surface, arteriole, venule and capillary intravascular hydrostatic pressure are equal in relation to the distance from the surface of the skin [217] , occluding the flow of blood to the periphery. As a larger proportion of light detected in the MOXY comes from surface tissue it is likely that the MOXY is more sensitive to pressure-induced changes in the dermis and subcutaneous oxygenation and blood flow. Again, the SR algorithm used to measure muscle TSI is less effective than the SRS method in the PortaMon in correcting for the effects of differences in blood flow and oxygenation in surface tissues. This finding has an important implication for researchers when undertaking repeated measures using the MOXY device, particularly when the removal and re-application of the NIRS device is required. Furthermore, athletes using similar devices to inform training intensity should standardise the external pressure applied to hold the instrument in place.

6.6.3 Test – Retest Reliability of Devices at Rest

This is the first study to report reliability data of the MOXY device. In the current study, we report absolute (the similarity between repeated measures (CV)) reliability. Previous CV of various NIRS monitors report resting TSI of the vastus lateralis between 2.3 – 5.8% [209,218–220]. These baseline TSI values are similar to that observed in the MOXY devices in our study (5.7 -6.2%). Interestingly, the present CV for the PortaMon devices are lower than that previously reported 1.8 - 2.5 vs. 4.7% [209]. However this variation may be due to differences in the precise anatomical location the device is placed, leg position (supine vs. seated), gender (male vs male and female) and health status of the participants (healthy vs chronic heart failure).

The acceptable test-retest reliability can be partially attributed to the homogenous group of participants used in the present study, with an adipose layer of < 7 mm. Caution is advised if using the devices on participants with greater adipose thickness and or when taking NIRS measures from an

alternative anatomical location. Furthermore, small differences in ambient and muscular temperature may influence day-to-day variability [189], as may slight changes in posture [97]. It is likely that in the present study, controlled environmental conditions, abstinence of exercise between testing days and a supine body position attenuated the variation observed, contributing towards the very strong test-retest reliability of the devices.

Resting TSI values in the brain are used as threshold values for clinical hypoxia in SR devices such as the INVOS 5100C, EQUANOX Classic 7600 and FORE-SIGHT Elite [221] although this has been criticised given the differences in patient skull geometry and consequently light transport. In muscle, the InSpectra used 2nd derivative spectroscopy to calculate a resting TSI in muscle that was suggested to report on tissue dysoxia in shock states [222]. This used the thenar (base of thumb) muscle due to the very small layers of overlaying adipose tissue in this area. In muscle groups more relevant to exercise physiologists and sports scientists, resting TSI values have been reported in calf muscle in compression clothing studies [97] and in the gastrocnemius during normobaric hypoxia [223]. When subjected to a normobaric hypoxic environment, the mean SRS-measured TSI change at rest, compared with the normoxic condition, was -2.5%. The authors report this finding to not statistically differ between conditions.

6.6.4 Comparing Devices during Isometric Exercise

There is no difference in ΔTSI between two models of the same device during isometric exercise. However, significant differences in ΔTSI are apparent when comparing MOXY vs. PortaMon. The MOXY devices report a greater absolute ΔTSI change when compared with the PortaMon at both 30 and 50% MVC. The ΔTSI observed with the current PortaMon devices is similar to that of a previous study, also utilising a PortaMon device [193], reporting a ΔTSI reduction of ~6 and 11% from baseline at 30 and 50% MVC respectively. Very few studies have utilised the MOXY device, however, of those available, the present ΔTSI at 30% MVC is similar to that observed in the gastrocnemius by supine individuals undertaking a plantar flexion exercise against a 6kg weight (~37% vs. ~38%) [224]

.

Both devices report appropriately that there is a decrease in muscle oxygenation during isometric exercise. However, unlike the situation for male participants at rest, there are significant differences in the extent of desaturation observed during exercise. Is it possible to determine which one is likely to be "correct"? In one sense there is no single "correct" value as, given the differences in source:detector separation, the NIRS and PortaMon are reporting on different regions of the muscle (and having to correct for different amounts of surface tissue). However, some limits can be set by more invasive methods. Comparing oxygen saturation differences between femoral venous and radial arterial blood with the ΔTSI changes observed in the present study may identify whether one device is more comparable to direct methods than the other. In trained participants femoral venous oxygen saturations of 21% and arterial oxygen saturation of 96% were measured following maximal leg extensions [225]. Assuming the NIRS signal is an approximately equal contribution of arterial, capillary and venous saturation, one would expect the absolute muscle oxygen saturation to be no lower than 55% in this case. Even allowing for the fact that femoral venous oxygen saturation represents the sum of all blood returning from the exercising leg, whereas the NIRS signal originate in the exercising muscle only [226], the almost 60% drop in TSI in the MOXY device at only 50% MVC seems rather high. On the other hand, as has been noted [227], the lack of a correction for the adipose layers can result in an underestimation of TSI changes using SRS methods. The variation between devices during the MVC exercise could be explained by the muscle contraction causing interference to the arterial inflow, therefore an increasing intramuscular pressure inducing ischemia. As such, the need to assess the devices during dynamic exercise provides an opportunity to understand the dynamic TSI range of the devices without the potential complication of ischemia.

6.6.5 Comparing Devices during Dynamic Exercise

During the incremental arm cranking task, both NIRS devices demonstrated a continuous decline in TSI as power output increases until volitional fatigue. Whilst some previous investigations have reported an early decline in muscle oxygen saturation during incremental arm exercise followed by a plateau at ~50% $\dot{V}O_{2max}$ [228], the general trend in TSI of the current study (Table 6-4) is closer to

studies where the biceps brachii TSI progressively decreases throughout arm cranking exercise [190]. Interestingly the continuous decline in mean TSI at each stage of the test (Table 6-4), masked significant individual variation; in one person (participant 3) an increase in TSI was seen following the initial fall. The fact that both devices showed the same unusual trend lends confidence to the idea, both that this individual has differences in the balance between flow and metabolism as exercise proceeds and that both Portamon and MOXY can detect this effect. By selecting participants and an anatomical location with very low ATT, and controlling external pressure at ~10 mmHg, variables previously identified to influence TSI values between devices were controlled. Nevertheless, we still observed a larger dynamic range in the study in the MOXY compared to the Portamon.

6.6.6 Comparing Devices during Occlusion/Reactive Hyperemia and the effect of physiological calibration

In an attempt to further explore the remaining differences we performed a "physiological calibration" of the two devices, comparing the dynamic exercise data from the biceps brachii to an individual participant and machine-specific 0-100% range determined by a nominal 0% following arterial occlusion and a nominal 100% following the reactive hyperemia after that occlusion. During the arterial occlusion (Fig. 6-7) both devices fell to a fixed low level below baseline within the first three minutes following occlusion and both showed reactive hyperemia following cuff release with the TSI rising above baseline. This contrasts with a recent study measuring TSI following three minutes arterial occlusion comparing in older adult patients (66 ± 9 year) scheduled for elective coronary artery bypass grafting surgery [207]. In these older patients three minutes occlusion was not enough to decrease TSI to a stable fixed baseline, probably due to a decrease in muscle oxygen consumption in this group compared to ours.

Despite choosing participants with a similar baseline TSI, significant differences were seen in ischemia and reperfusion between the Portamon and the MOXY. The range (Hyperemia MAX minus Occlusion MIN) in the Portamon was Δ43.7 % whereas in the same participants the MOXY change was Δ74.3%. However, when calibrated against the physiological range observed during and post

ischemia, there is now no statistically significant difference between devices during the arm crank exercise, nor the maximum value obtained during reactive hyperemia post exercise. This suggests that both methods are equally good at measuring muscle oxygenation changes in males with low ATT.

6.6.7 Comparing Algorithms

The PortaMon uses the well-established modified Beer-Lambert method for measuring changes in chromophore concentrations [229] and SRS for measuring absolute tissue oxygen saturation [205]. The MOXY uses Beer-Lambert and a proprietary SR algorithm based on a US patent [230]. Pathlength data is generated from a Monte Carlo Model, smoothed and used to generate a matrix of diffuse reflectance data at discrete values of tissue and sensor optical properties. This matrix is then used to convert the measured diffuse wavelength data to tissue optical properties, from which the oxygen saturation measure can be calculated. In their basic form, neither SRS nor SR algorithms take into account prior knowledge about individual differences in, for example, adipose layer thickness, resulting in some of the variability seen in this study. Some simple NIRS devices, such as the ASTEM NIR_{SRS} have incorporated adipose layer measurements to improve the accuracy of their algorithms [231]. In principle, both PortaMon and MOXY methods described in this paper could make similar adjustments. Previous authors have incorporated adipose tissue thicknesses of individual participants as measured by ultrasound combined with SRS measurements in a two layer (adipose/muscle) Monte Carlo model to directly calculate muscle μ_a [227]. A similar individualized measure should be possible for the MOXY device, decreasing the dependence of the TSI value on adipose layer thickness.

The MOXY device reports a significantly larger dynamic range when an arterial occlusion is applied, despite a shorter source:detector length when compared with the PortaMon. It has been suggested that the ischemic stimulus is more extensive in the muscle compared with the sub-dermal tissue [201], therefore, the greater dynamic range reported by the MOXY may be related to the spatial resolution method enabling a greater muscle contribution than the SRS despite the smaller source:detector separation in the MOXY. However, it is also likely in part a function of algorithm optimisation and specialisation. The MOXY is designed to be used on muscle and could reasonably be expected to have

been optimised for this system. The Portamon, although designed to be used on muscle, makes no concessions or alterations to the basic SRS algorithm compared to similar Artinis devices used to measure brain function.

The minimum and maximum raw TSI values reported for the PortaMon (Δ43.7%) are similar to that previously reported for the NIRO 200-NX [207] following an arterial occlusion applied at the upper arm (Δ33%). This finding is unsurprising given that both the NIRO 200-NX and PortaMon both use SRS methods. However, the larger dynamic range reported by the MOXY (Δ74.3%) surpasses that of alternative SR devices such as the FORE-SIGHT elite (Δ 46%) and INVOS5100C (Δ 36%) [207]. This illustrates the difficulty in comparing different SR devices which use different algorithms and are likely sensitive to differences in the source:detector separation even when determining basic calibration ranges. The INVOS (3cm and 4 cm) and FORESIGHT (2.5cm and 5 cm) use significantly larger source:detector separations than the MOXY (1.2cm and 2.5cm) and, given their clinical interests, their algorithm development has likely focused more on brain than muscle measurements. However, in the absence of devices from these manufacturers with similar source:detector separations and the proprietary nature of the individual algorithms, it is impossible to speculate further as to the cause of these differences.

6.6.8 Real world applications

The MOXY is designed to be of use to individuals in a variety of sporting environments. There have been suggestions as to how NIRS might be of use for individual athletes and coaches in, for example, tracking and optimising training. However, in many cases, these have merely sought to mimic currently available tools, such as lactate thresholds, albeit with the benefit of being non-invasive [232,233]. Even then, differences in optical properties of individuals make these measurements unreliable in many cases [234]. No one has yet been able to demonstrate a specific benefit of using muscle NIRS to track training in an individual. What is required is a proper randomised trial comparing the use of NIRS to optimise training with current standard methods. The advent of relatively low-cost devices, such as the MOXY, makes such a trial more accessible. However, this

work here suggests that, even if successful, the results of such a trial might remain specific for the NIR device used and not necessarily transferable to other spectrometers. This present study has focused solely on the TSI values produced by the MOXY and PortaMon devices. Future studies could address the tHb values reported by the MOXY device and compare these with the (rarely reported) scaled tHb that can be derived from SRS methods.

Subcutaneous fat is known to have a large impact on NIRS signal. Whilst high ATT results in less light absorption and therefore a stronger signal, the metabolically inactive fat tissue, coupled with lower haemoglobin levels will result in less signal change [235] i.e. a blunted dynamic range. Given the observed influence of high ATT on resting TSI in the MOXY device and the small source:detector separation used, it is not clear how valid the current algorithm is for use in athletes with higher ATT; this includes a significant number of female athletes. In order to fully utilize the MOXY device in individuals with ATT >7 mm, the source-detector distance should be increased accordingly. Commercial muscle NIRS devices with larger source-detection distances are widely available [191]. Future studies should measure TSI trend during dynamic exercise of those with ATT between 7 - 15 mm and determine whether the influence of ATT can be removed by applying an ischemic calibration as has been shown previously for muscle oxygen consumption measurements previously [236].

6.7 Conclusion

This study shows that both MOXY and PortaMon devices produce acceptable TSI measures during supine rest and demonstrate a similar trend during dynamic exercise under appropriately controlled conditions in specific participant groups. During ischemia (arterial occlusion and isometric contractions) the MOXY device reports a greater raw dynamic range when compared with the PortaMon However, by applying a physiological calibration following an arterial occlusion, the MOXY and PortaMon devices report similar changes from baseline during arm crank exercise. Due to the limitations of calibrating NIRS, it is not possible to determine which device is a more accurate measure of absolute muscle oxygen saturation; Although the PortaMon demonstrates a greater

repeatability at rest, this may simply be reflective of the smaller dynamic range observed. The MOXY is marketed at athletes and coaches and priced accordingly (< $1,000), whereas the higher priced PortaMon (< $10,000) tends to be used primarily by research scientists. For the researcher, the PortaMon has the advantage of measuring and reporting more NIRS parameters. At least in the case of vastus lateralis measurements, the PortaMon also appears to be less sensitive to variations in adipose layer thickness and applied external pressure. We recommend the application of the MOXY device primarily on individuals with a low adipose tissue thickness, and that the external pressure applied to hold the device in place is either standardised upon each application or kept below 20 mmHg.

7 Compression tights have no effect on economy of treadmill running at race pace.

7.1 Rationale

The capacity for compression tights to aid running economy at particular relative exercise intensities (Chapter 5) and when the interface pressure is above a particular threshold (Chapter 4) has been reported. However, their capacity to influence running economy at race speed is unknown and arguably of most relevance to endurance athletes. Moderately trained distance runners were assessed at running speeds associated with their most recent race performance, with and without compression tights. Multiple physiological parameters were collected, including tissue oxygen saturation using the MOXY device (Chapter 6). The decision to use the MOXY device rather than the PortaMon was primarily driven by its lighter weight, thus less likely to impact running gait during submaximal exercise.

7.2 Abstract

The aim of the present study was to examine whether compression tights modify running economy (RE), kinematics and muscle oxygenation (SmO_2) in recreational runners. Thirteen males and five females completed two RE tests at a speed corresponding to a recent race time (10k, half marathon or marathon distance) during a single laboratory session. Test order was randomised between the treatment trial of compression tights and control trial with running shorts. RE was determined by oxygen consumption and carbon dioxide expiration during the final three minutes of each fifteen minute running task on a treadmill. SmO_2 was measured using portable, wireless near-infrared spectroscopy devices positioned on the calf and thigh. Vertical oscillation and ground contact time were determined from a tri-axial accelerometer device. Skin temperature at the calf and thigh were

measured continuously. Ground contact time was shorter with compression (238 ± 20 ms) compared with control (243 ± 19 ms) trials (P = 0.03), however no differences in RE, SmO_2, vertical oscillation, HR or skin temperature were revealed. Gait variability was calculated as the intra-individual standard deviation of kinematic variables during the last 3 min of running. Wearing compression tights decreases ground contact time but does not alter the energetics of running at a competitive race pace. It appears the individual response to compression tights is most improved in participants with a low vertical oscillation and exhibit less stride-to-stride variation in vertical oscillation.

7.3 Introduction

Wearing CGs during exercise has gained popularity within the last two decades [237]. World records have been set by athletes donning compression garments, reinforcing the link between compression clothing and elite performance [52]. Although the world records are undoubtedly the result of talent and training, athletes choose to wear these garments in the belief they will aid performance.

Despite the popular use of CGs among elite and moderately trained athletes, the prevailing consensus indicates only small improvements in time to exhaustion tasks (Hedges g = 0.27 ± 0.33) [4] or during middle distance running (800 – 3000 m) (weighted mean improvement = 6.1 s) [69]. Wearing compression garments during 5 and 10 km runs [52,60], 15 km trail running [71] and a marathon [64] resulted in no ergogenic benefit. The type of garment used in these time-trial performance tests included either stockings or socks and have not included full length tights. Compression tights have been shown to improve variables related to running performance such as running economy [9], muscle oxygenation [10] and running kinematics [80]. Intriguingly, when compression tights have produced a positive effect, the recorded garment pressure was ~20 mmHg at the calf and 13 – 18 mmHg at the thigh. Perhaps this is indicative of a required pressure threshold to elicit physiological and biomechanical changes during endurance running. In support of this observation, a minimum pressure threshold required to improve venous return of 17.3 mmHg at the calf and 15.1 mmHg at the thigh

was proposed [12]. At or above this pressure, compression may narrow superficial blood vessels and modulate haemodynamic factors [142].

Running economy (RE) defined as the metabolic cost of travelling a given distance is a useful indicator of endurance performance [168]. Referred to as a multifactorial measure, RE is influenced by biomechanical, cardiopulmonary, metabolic and neuromuscular systems [110]. In heterogeneous populations with varying $\dot{V}O_{2max}$ values, a strong positive relationship exists between $\dot{V}O_{2max}$ and running performance. However, RE is an important determinant of performance among runners who possess similar $\dot{V}O_{2max}$ values [168]. The benefit of possessing a good RE is evident for elite [167] and moderately trained individuals [238]. Marginal improvements in RE are directly associated with better distance running performance and therefore strategies to improve energy cost are of great interest to runners [238]. Compression tights are shown to elicit a positive effect on RE in recreationally trained individuals above a relative exercise intensity of 77.7% $\dot{V}O_{2max}$ (see Chapter 5). However, whether compression tights improve RE at competitive running speeds requires further investigation.

The aim of the present study was to examine whether compression tights modified RE, substrate utilization, kinematics and muscle oxygenation of moderately trained runners. Garment pressure was targeted to achieve the minimal pressure threshold and RE assessment was completed at a speed that corresponded to an individual's most recent race time over 10k, half marathon or marathon distance.

7.4 Methods

7.4.1 Participants

Ethical approval was received from the University of Essex ethical committee. Participants provided written informed consent in accordance with the Declaration of Helsinki. Thirteen male and five female volunteers provided written informed consent before participation in the study (Table 7-1). All participants were moderately trained runners and had completed a 10,000-m, half marathon or full marathon within the previous 12 months. A moderately trained runner was defined as a runner who

had engaged in a systematic training program of endurance running for at least one year and completing between 10 – 45 km•week^{-1}. At the time of investigation, all participants were completing ≥3 training sessions a week and free from musculoskeletal injury within the one month previous.

Table 7-1 Descriptive characteristics of participants, training volume and best race performances in previous 12 months (Mean ± SD).

	Males (n=13)	Females (n=5)
Age (years)	37.6 ± 10.0	39.2 ± 7.7
Height (m)	1.77 ± 0.07	1.65 ± 0.08
Body Mass (kg)	72.0 ± 8.5	59.8 ± 6.1
Weekly training distance in past 6 months (km)	42.9 ± 18.4	27.4 ± 8.7
Event average time		
10,000 m (min:s)	41:33 ± 4:58 (n=9)	49:49 ± 3:30 (n=4)
Half marathon (hr:min)	1:38 ± 0:12 (n=10)	1:47 ± 0:12 (n=3)
Marathon (hr:min)	3:33 ± 0:20 (n=6)	3:35 (n=1)

Note: some participants (n=11) reported personal bests in more than one event

7.4.2 Compression Garments

Full-length compression tights covering the body from ankle to waist were used in the investigation (Skins ™ A400, Riverwood, Australia). Participants were required to wear two compression tights on top of each other to achieve a target interface pressure of ~20 and ~15 mmHg at the calf and thigh respectively. Garment size for both tights was selected in accordance with the manufacturer's sizing guide. The garments were made from warp knitted fabrics, with the fibre reported as 76% nylon and 24% elastane, fabric thickness as 0.57 ± 0.01 mm and fabric weight 199.33 ± 0.57 g/m^2 (See Chapter 3 for fabric specification). The interface pressure exerted by the CGs were evaluated by the PicoPress® (Microlabs, Italy) pressure monitor (coefficient of variation = <5% at 20 mmHg [1]). Pressure measures were recorded at two anatomical locations (posterior orientation of the maximal calf girth

and anterior thigh at the mid-point between mid-trochanterion-tibiale laterale). The control condition consisted of loose fitting running shorts, thereby providing a comparison between compression tights and garments typically worn by recreational runners.

7.4.3 Experimental Design

Participants completed a single experimental session in a controlled laboratory environment (temperature: 18 ± 1.0° C). In the 24 hours prior to testing, participants were asked to refrain from exercise, caffeine and alcohol intake. As participants could not be blinded to wearing CGs, a questionnaire was completed defining their a priori beliefs and experiences regarding compression garments [94]. Two separate running tests took place during the session to assess the impact of compression tights on energy cost, muscle oxygenation, running kinematics, heart rate and skin temperature. Participants wore compression tights and control garments for each test in a randomised and counterbalanced manner (Figure 7-1).

Body mass and stature was initially recorded using digital platform scales (SECA, Model 813, Birmingham, UK) and a stadiometer (SECA, Model 213, Birmingham, UK). Skinfold thickness was measured at the vastus lateralis and gastrocnemius of the dominant leg using skinfold callipers (Harpenden HSK-BI, British Indicators Ltd, UK). Participants were then fitted with a heart rate monitor, skin thermistors and two portable muscle oxygenation sensors. Participants performed 15 min supine rest on a medical examination bench prior to the exercise task. Each run test consisted of a 15 min run on a motorized treadmill (Quasar; HP Cosmos, Nussdorf, Germany) at a speed corresponding to the individuals most recent 10 k, half marathon or marathon time. The calibrated treadmill gradient remained at 1% throughout. Convective airflow was provided throughout the running task by a fan (~400 mm diameter,~2 $m \cdot s^{-1}$) at a distance of 1 m in front of the treadmill. Between each test, participants remained seated for 15 min followed by a further 15 minutes supine with water available to consume ad-hoc. During each 15 min run test, heart rate, ground-contact time, vertical oscillation, skin temperature, respiratory gases and indices of muscle tissue oxygenation were measured continuously.

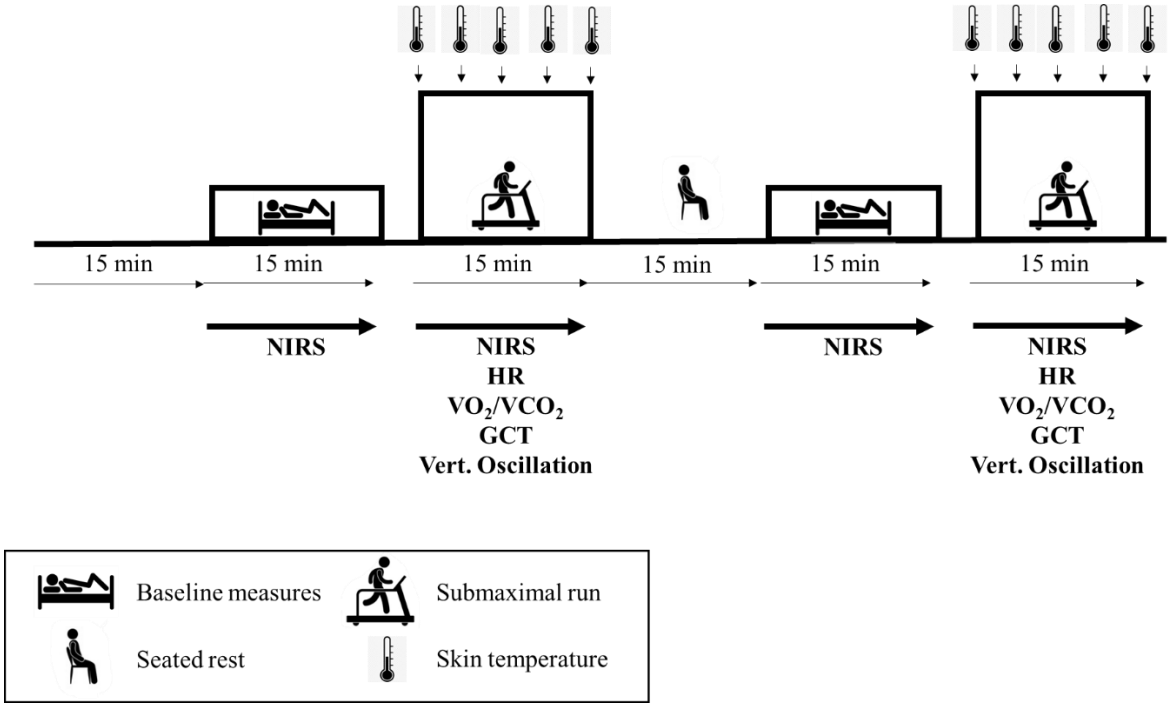


Figure 7-1 *Schematic representation of experimental design.* NIRS, near-infrared spectroscopy; HR, heart rate; $\dot{V}O_2$, oxygen consumption; $\dot{V}CO_2$, expired carbon dioxide; GCT, ground contact time; Vert, vertical.

7.4.4 Experimental Procedures

Cardiovascular measures

Throughout each run test, participants wore a dead-space mask with an impeller turbine assembly (Hans Rudolph, Kansas, USA) and gas concentrations continuously sampled via a capillary line. Concentrations were determined by electrochemical (O_2) and infrared (CO_2) analysers (Vyaire CPX, Mettawa, Illinois, USA). Prior to each test, the gas analysers were calibrated with gases of known concentration (16% O_2 and 5% CO_2), and ambient air. The digital volume transducer was connected to the housing blower and calibrated automatically using both high and low flow parameters. Mean oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) were averaged from second-by-second data over the final 3 min of each run test. Second-by-second $\dot{V}O_2$ and $\dot{V}CO_2$ data were used to determine running economy (RE) as caloric unit cost ($kcal \cdot kg^{-1} \cdot km^{-1}$), carbohydrate oxidation

(CHO_{OX}) and fat oxidation (FAT_{OX}) ($g \cdot kg^{-1} \cdot km^{-1}$) using equations for moderate to high intensity (50-75% $\dot{V}O_{2max}$) [173]. To ensure principally aerobic contribution to energy expenditure, we excluded participants if respiratory exchange ratio (RER) >1.00 during the final 3 minutes of the submaximal run. Both RE ($kcal \cdot kg^{-1} \cdot km^{-1}$) and $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$) are reported, enabling comparison with previously published data.

Heart rate (HR) was continuously monitored using a Garmin HR monitor (Forerunner 720XT, Garmin Ltd, Schaffhausen, Switzerland). Mean HR was averaged from second-by-second data across the final 3 min of each run test.

Near-infrared spectroscopy

Muscle oxygenation was assessed using near-infrared spectroscopy (NIRS). The MOXY monitor (Fortiori Design LLC, USA) reports physiologically credible changes in tissue oxygenation (SmO_2) and total haemoglobin (tHb), providing insight into the balance between oxygen supply and consumption [239]. The MOXY employs four wavelengths of NIR light at 680, 720, 760, 800 nm [230] and the sensor contains a single light emitting diode (LED) and two detectors in placed 12.5 and 25.0 mm from the source.

One device was positioned on the belly of the vastus lateralis midway between the greater trochanter and the lateral epicondyle of the femur, the other at the maximal calf girth on the posterior aspect of the gastrocnemius. To ensure the optodes and detector did not move relative to the participants' skin, the devices were fixed into position using a waterproof adhesive tape. In addition, bodily hair at or around the sensor placement area was removed from the skin and participants were asked not to moisturise the area on the day of testing. In the compression condition, 6 cm diagonal incisions were made in the garments to expose the NIRS devices. Black crepe bandage was wrapped around the leg to secure the NIRS devices and ensure that no external light would be received by the device detectors. A portable pressure monitor (PicoPress, Microlabs, Italy) was used to ensure the pressure applied by the bandage was equal to the pressure initially applied under the CGs (~20 mmHg = thigh;

15 mmHg = calf), thereby minimising the influence of additional unwanted pressure applied by the bandage (Figure 7-2). In the control condition, bandage pressure was maintained at 8mmHg to minimise ischemia induced changes in SmO_2 and tHb [239]. During all testing, the system was connected to a personal computer via a commercially available software programme (Peripedal ©) to provide a graphic display of the data. Data acquisition (2 Hz) was obtained from the sensors internal memory and data-sets were smoothed by calculating the 3 second moving average. Due to potential differences in resting values between run tests, SmO_2 was reported as a change from baseline. Baseline SmO_2 and tHb were established as the final 30 seconds of the 15-min supine rest period prior to each run test. During each run test, the minimum SmO_2 and tHb in the initial 1 min was identified (10-s average) in addition to the final 1 min average at the end of the 15 min treadmill run. These values were subtracted from the baseline to provide a delta (Δ) 1 min and Δ15 min value. The difference between Δ1 min and Δ15 min value was calculated (Δdiff) to determine the muscle oxygenation response for the final 14 minutes of the run task. To ensure sufficient optical density penetrating the adipose layer, participants with an adipose tissue thickness (ATT) <15 mm were excluded from analysis [240]. ATT was calculated as 0.5 × mean skinfold thickness.

1. Interface pressure measured where MOXY will be positioned.
2. 6 cm incision cut into garment
3. MOXY attached with tape
4. Crepe bandaging wrapped around the leg to hold the MOXY in place, matching interface pressure initially measured before incision

Figure 7-2 *Method to ensure interface pressure of garment is maintained despite cutting an incision into fabric. Image for illustrative purposes showing NIRS device positioned at the vastus lateralis, prior to crepe bandage application.*

Running kinematics

Participants wore a heart rate strap equipped with a tri-axial accelerometer (HRM-Run; Garmin Ltd, Schaffhausen, Switzerland). The strap was placed on the xiphoid process of the sternum. Output was sent wirelessly to a wristwatch (Forerunner 920XT, Garmin International Inc., Olathe, KS) via a 2.4 GHz ANT+ system. Vertical oscillation and ground contact time (GCT) were calculated using the proprietary algorithms of the Garmin Connect software [241], previously reported as valid and reliable measures [242] compared with a motion-analysis system. Mean vertical oscillation (cm) and GCT (milliseconds) were averaged from second-by-second data over the final 3 min of each run test. Vertical oscillation and GCT variability was calculated as the standard deviation for an individual during the final 3 min of the submaximal run.

Temperature measurement

Skin temperature (T_{sk}) was recorded throughout the run test by taping temperature sensors (Libra medical Ltd, Model ET402, Ascot, Berks, UK) adjacent to the NIRS devices at the gastrocnemius (calf) and vastus lateralis (thigh). T_{sk} was recorded each minute and 3 min averages calculated and used for data analysis.

Subjective Questionnaire

Participants were asked seven dichotomous questions and answers were summed to give an overall belief score [94]. Lower scores would indicate little or no experience with and negative opinions on the effectiveness of CGs.

7.4.5 Statistical Analysis

Data are presented as mean and 95% confidence intervals (95% CI) for all dependent variables. Paired differences between conditions for dependant variables were initially tested for normality using the Shapiro-Wilk test. Analysis of RE, HR, SmO_2, vertical oscillation and GCT was performed by a paired samples t-test to measure potential significant differences between two means. To assess differences in T_{sk} at different time intervals, a 2 x 5 repeated-measures ANOVA was conducted. Fishers LSD test was used for *post hoc* pairwise comparisons. In addition, the magnitude of the differences between each condition was calculated using Cohen's *d* effect size with thresholds for small, moderate and large effects as 0.2, 0.5, and 0.8 respectively. Pearson's product-moment correlation analysis was performed to examine the association between belief score and RE differences between garment conditions. Statistical tests were processed using the statistical package SPSS (Version 18) and Microsoft Excel (Microsoft Corporation TM, Redmond, WA, USA). The level of statistical significance was identified by an alpha value of $P < .05$.

7.5 Results

The pressure applied by the compression tights was 17.8 [95% CI; 15.9 - 19.7] mmHg and 13.1 [95% CI; 11.8 - 14.3] mmHg at the calf and thigh respectively. One participant recorded an RER > 1.00 during the 15 min treadmill run. As a consequence, all data acquired from that individual was removed prior to analysis.

No difference was found for cardiovascular measures of RE, RER, $\dot{V}O_2$, HR (Table 7-2). In addition, correlation analysis revealed no association between belief scores and changes in RE (r = .29; P = 0.27) (Figure 7-3). Figure 7-4 displays the change in running economy for each participant as a violin plot. A difference was observed between garment conditions for GCT (t (16) = 2.34, P = 0.03), indicating participants exhibited a shorter contact time with compression tights, however vertical oscillation remained unchanged.

Table 7-2 Cardiovascular responses and running kinematics data during 15 min run with and without compression tights (Mean [95% CI]).

	Control	Compression	*P*-value	*d*=
Cardiovascular parameters				
RE ($kcal \cdot kg^{-1} \cdot km^{-1}$)	1.05 [1.01-1.10]	1.05 [1.02-1.09]	0.91	0.03
RER	0.92 [0.90-0.95]	0.92 [0.90-0.95]	0.69	0.10
$\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	41.9 [39.4-44.4]	42.1 [39.2-44.9]	0.69	0.10
CHO_{OX} ($g \cdot kg^{-1} \cdot km^{-1}$)	2.60 [2.28-2.91]	2.59 [2.28-2.90]	0.88	0.04
FAT_{OX} ($g \cdot kg^{-1} \cdot km^{-1}$)	0.37 [0.23-0.51]	0.38 [0.25-0.51]	0.62	0.12
HR (bpm)	153 [145-160]	155 [150-160]	0.30	0.26
Running kinematics				
Vertical oscillation (cm)	9.9 [9.0-10.8]	10.2 [9.2-11.1]	0.29	0.27
GCT (ms)	243.1 [233.0-253.2]	237.7 [228.0-247.3]	0.03*	0.57

Values shown as mean [95% CI]. * = statistically significant difference between conditions (P<0.05); *d* = Cohen's effect size; RE = caloric unit cost; RER = respiratory exchange ratio; $\dot{V}O_2$ = Oxygen consumption; HR = Heart rate; GCT = Ground contact time. Mean [range] running speed the same in both conditions = 11.9 [10.3 - 14.8] $km \cdot h^{-1}$.

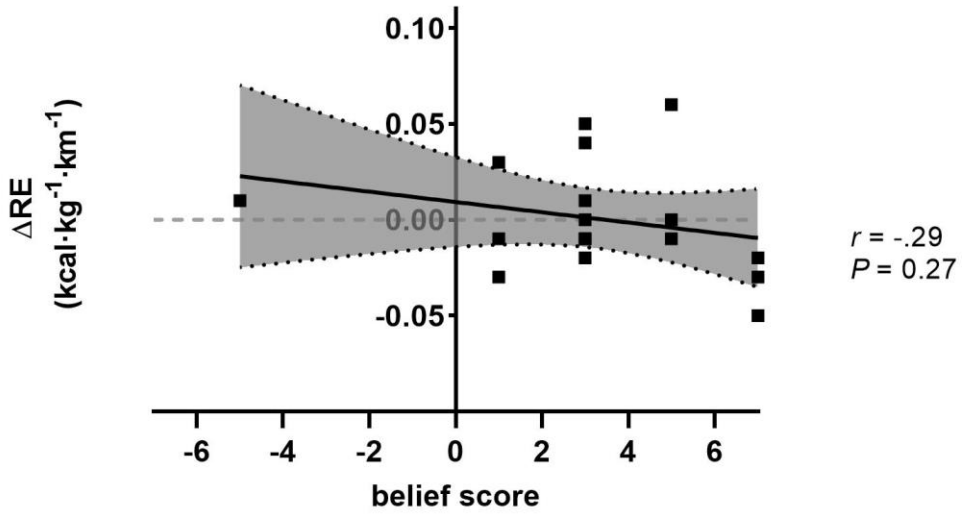


Figure 7-3 *Change in running economy (ΔRE) as a function of belief score.* ΔRE calculated as control minus compression. 95% confidence interval indicated by shaded area.

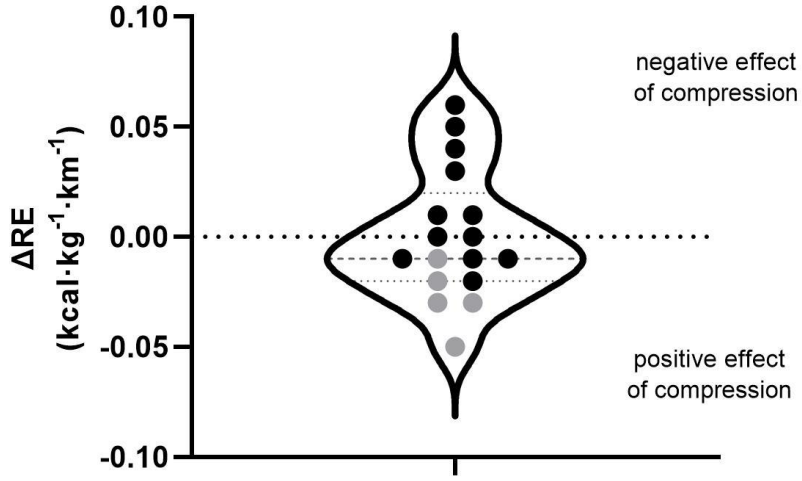


Figure 7-4 *Violin plot showing the effects of compression tights on running economy (ΔRE).* ΔRE calculated as control minus compression. Median (dashed) and quartile (dotted) ranges displayed for whole group. Individual data points presented for male (black) and female (grey) participants.

Compression produced heterogeneous responses in terms of ΔRE (ΔRE range -5.6 – 3.8%) (Figure 7-4). *Post hoc* secondary analysis was conducted using participants with the greatest improvements

[responder] (n = 4; ΔRE range 1.9 – 3.8%) and decrements [non-responder] (n = 4; ΔRE range -5.6 – -3.6) in RE to identify whether kinematic variables (vertical oscillation and GCT) explained the individual response to compression tights. Table 7-3 shows responders had less vertical oscillation (d = 1.30) and less variability in stride-to-stride vertical oscillation (d = 0.86). However, such large differences were not observed with GCT between participants who improved RE and those who worsened (Table 7-4). Intriguingly, participants with improved RE reported small increases in GCT (d = 0.21) and stride-to-stride GCT variability (d = 0.42).

Table 7-3 Comparison of vertical oscillation (cm) and intra-individual variability (SD) during the compression trial between responders and non-responders.

	Responders (n=4)	Non-responders (n=4)	P-value	d=
Vertical oscillation (cm)	9.6 ± 1.6	11.7 ± 1.8	0.12	1.30
Vertical oscillation variability	0.3 ± 0.1	0.5 ± 0.4	0.28	0.86

Values are mean ± SD

Table 7-4 Comparisons of ground contact time (ms) and intra-individual variability (SD) during the compression trial between responders and non-responders.

	Responders (n=4)	Non-responders (n=4)	P-value	d=
GCT (ms)	232.4 ± 27.4	228.1 ± 10.2	0.78	0.21
GCT variability	3.5 ± 1.0	3.1 ± 1.0	0.58	0.42

Values are mean ± SD

Due to data signal drop out, SmO_2 and tHb data were available for 14 participants at the vastus lateralis and for 15 participants at the gastrocnemius. There were no differences in SmO_2 and tHb between garment conditions at any of the time points or the change (ΔDiff) between 1 and 15-min (Table 7-5 + 7-6).

For T_{sk} at the calf and thigh, there were significant main effects for time ($p < 0.001$) but not garment ($p = 0.11$ and $p = 0.62$) or their interaction ($p = 0.47$ and $p = 0.80$) (Fig 7-5).

Table 7-5 SmO_2 (%) data during 15 min run with and without compression tights.

	Control	Compression	*P*-value	*d*
Gastrocnemius (n=15)				
Baseline	70.0 [62.8-77.3]	63.8 [55.3-72.3]	0.34	0.25
Δ1 min	-45.9 [-52.9- -39.0]	-44.7 [-53.6- -35.9]	0.84	0.06
Δ15 min	-26.7 [-36.4- -17.1]	-24.8 [-36.7- -12.9]	0.74	0.09
Δdiff	19.2 [12.0-26.4]	19.9 [13.0-26.8]	0.75	0.09
Vastus Lateralis (n=14)				
Baseline	70.5 [63.9-77.1]	67.9 [61.3-74.5]	0.42	0.22
Δ1 min	-35.0 [-39.7- -30.3]	-30.5 [-35.9- -25.1]	0.15	0.41
Δ15 min	-30.4 [-38.3- -22.5]	-23.7 [-30.7- -16.6]	0.14	0.43
Δdiff	4.7 [-0.5-9.8]	6.8 [2.0-11.7]	0.31	0.28

Δdiff = difference between Δ1-min and Δ15-min value. Values are mean [95% CI].

Table 7-6 tHb (arbitrary units) data during 15 min run with and without compression tights.

	Control	Compression	*P*-value	*d*
Gastrocnemius (n=15)				
Baseline	12.5 [12.2-12.8]	12.6 [12.3-12.8]	0.36	0.24
Δ1 min	0.0 [-0.12-0.12]	-0.07 [-0.23- 0.09]	0.80	0.07
Δ15 min	-0.08 [-0.23-0.07]	-0.15 [-0.34- 0.04]	0.63	0.13
Δdiff	-0.08 [-0.17-0.02]	-0.08 [-0.19-0.02]	0.84	0.05
Vastus Lateralis (n=14)				
Baseline	12.7 [12.5-12.9]	12.7 [12.5-13.0]	0.66	0.12
Δ1 min	-0.11 [-0.21-0.0]	-0.14 [-0.21- -0.08]	0.36	0.25
Δ15 min	-0.07 [-0.21-0.07]	-0.08 [-0.17- 0.01]	0.84	0.05
Δdiff	0.04 [-0.02-0.09]	0.07 [0.01-0.12]	0.12	0.44

Δdiff = difference between Δ1 min and Δ15 min value. Values are mean [95% CI].

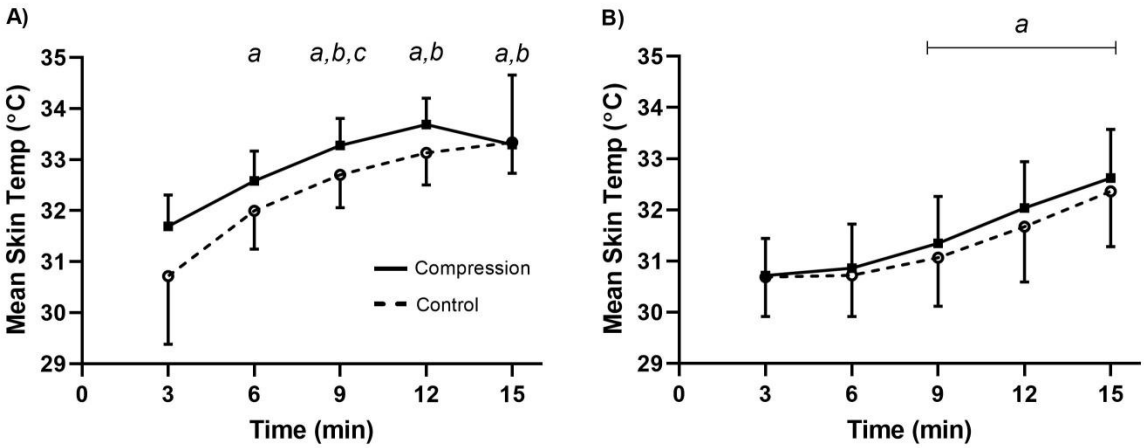


Figure 7-5 *The effects of compression garments on skin temperature of the calf (A) and thigh (B) during 15 min race pace running.* [a] Significantly Different to 3 min ($P<0.05$). [b] Significantly Different to 6 min ($P<0.05$). [c] Significantly Different to 12 min ($P<0.05$).

7.6 Discussion

The current study investigated the influence of wearing compression tights on physiological parameters during submaximal running at long-distance race speed. In the present investigation, no difference in any cardiovascular, NIRS or skin temperature measure was revealed between garment conditions. GCT was shorter with compression tights however vertical oscillation remained unchanged.

Analysed as a whole group, RE was unaffected by wearing compression tights and consistent with previous findings. Dascombe *et al.*, [10] reported no change in RE or $\dot{V}O_2$ at speeds between 10 – 18 $km \cdot h^{-1}$ with well-trained middle-distance runners. The interface pressure reported at the calf (19 mmHg) and thigh (~14 mmHg) appear comparable with the present study; however pressure assessment was conducted with the Kikuhime pressure monitor. Chapter 3 identifies a systemic bias in the interface pressures reported by the Kikuhime, overestimating the values in comparison to the PicoPress and a medical reference standard. It is likely that the garments applied an interface pressure similar to that of the tights used throughout this thesis as the same brand (SKINS) were worn. It is

worthwhile noting that in the present study, two garments were worn simultaneously to achieve the desired pressure threshold previously postulated [12]. However, adherence to this threshold did not reveal changes in any cardiovascular parameter measured. Similarly, in well-trained runners and triathletes, there was no effect of compression tights targeting an interface pressure of 20 mmHg on $\dot{V}O_2$ during a 15 min run at 70% $\dot{V}O_{2max}$[58]. However, in this instance, interface pressure was not directly measured so it remains unknown whether the targeted pressure of 20 mmHg was achieved. The current findings support the literature regarding compression tights having no effect on RE or any other cardiovascular measures in moderately trained runners. Participants were required to run at a pace of their recent best time in 10,000 m, half marathon or marathon distance. It is conceivable that this competition pace is a speed that participants regularly train at and therefore athletes are already "most" economical at this intensity[243]. In support of this, Varela-Sanz *et al.*,[81] reported no change in $\dot{V}O_2$ at half-marathon pace with compression stockings, suggesting that athletes already select the most economical locomotion style at competition pace and deviating from this style will likely result in significant decrements in RE.

7.6.1 Variation in Running Economy

Small improvements in RE are associated with better running performance. As little as 1% change in submaximal $\dot{V}O_2$ is reported to have significant performance implications [6,109]. The present study included both male and female participants grouped together. Interestingly, when analysed separately, males report a mean increase of 1.2% in $\dot{V}O_2$ with compression tights, whereas the five female participants reduced $\dot{V}O_2$ by 2.4% (Figure 7-2). Previously reported intra-individual variation of oxygen cost in moderately trained runners at 88% of the lactate breakpoint was 2.0% [166]. Furthermore, female distance runners reported a variation in $\dot{V}O_2$ between 1.4 – 2.2% at speeds between 11.2 – 14.8 $km \cdot h^{-1}$ [244]. The change observed among female participants in the present study is greater than previously reported intra-individual variation. This suggests that the observed change may be of practical benefit and requires further investigation with an adequately powered study. If the influence of compression tights on running economy differs between male and female

runners, this could be associated with gender differences in lower extremity mechanics during running [122].

7.6.2 Fabric Considerations

It is widely reported that CGs can positively influence physiological parameters such as blood flow velocity [3] and proprioceptive capability [237]. However, an overlooked area associated with compression clothing is the additional mass of garments, thereby adding an increased metabolic cost. The additional weight of a garment may negate any potential benefit caused by increased transmural pressure and stimulation of mechanoreceptors brought about by compression. Previous studies show an added shoe mass of ~100g per shoe increases metabolic rate by 1% [245,246]. It is conceivable that the total mass of the two garments (~350g) worn in the present study may have degraded running economy.

7.6.3 Subjective Measures

The participants perception of CGs may influence the individual response [163]. Belief in sports compression did not influence ΔRE. This is unsurprising given the majority of participants (n = 13) reported positive belief scores (score range 3 – 7), with only one participant showing negative responses (score range -7 – -3) and three exhibiting neutral responses (score range -2 – 2). In contrast, Stickford *et al.*,[94], reports an inverse correlation between belief scores and changes in $\dot{V}O_2$, revealing that highly trained distance runners reporting more positive feelings about CGs produced greater decrements in submaximal $\dot{V}O_2$ when compression stockings were worn. Dramatic placebo effects have been previously reported with athletic footwear, influencing vertical jump performance[247] and following an induced expectation, a sleeveless compression top reduced participants perception of exertion during a cycling task. It remains unknown whether an induced expectation or treatment expectation can bring about changes in RE.

7.6.4 Cardiac Parameters

No significant garment effect on heart rate during submaximal exercise was observed in the present study. This observation is in agreement with previous investigations, who reported that heart rate is

unaffected by compression tights when running at 110% $\dot{V}O_{2max}$ [248], or with compression stockings during a 10km time trial [52]. In addition, a recent meta-analysis revealed that CGs have little to no influence on cardiac parameters such as heart rate, cardiac output or stroke volume (g = 0.08 ± 0.37) [4]. Despite reported increases in venous flow velocity and venous return when compression is applied at rest, increased cardiac output due to exercise is likely to supersede minor changes to flow velocity caused by compression. This is perhaps indicative of the effectiveness of skeletal muscle pumps and venous valves during continuous dynamic exercise [93].

7.6.5 Skin Temperature

Skin temperature was not different between garment conditions at the gastrocnemius or vastus lateralis at any time point during the exercise task. This is of particular interest considering participants wore two compression tights and previous investigations have reported higher skin temperatures under single layer CGs [72,93]. A noteworthy increase in skin temperature (~1°C; d = 0.48) was observed at the gastrocnemius after three minutes of exercise; however the between-garment difference diminished as the duration of exercise continued. Elevated skin temperatures associated with compression clothing are traditionally attributed to lower air circulation and convection, thereby reducing heat dissipation. However it is plausible that the convective air-flow and fabric properties mitigate potential changes in skin temperature. Indeed, in the present study, the skin thermistors were placed at an anterior (vastus lateralis) and posterior (gastrocnemius) orientation. The convective air flow delivered by the fan may explain the difference in skin temperature between measuring locations. It is suggested that thermal effects may be more pronounced during prolonged high-intensity or intermittent exercise, without constant air-flow, however further research is required to substantiate this theory [93].

7.6.6 Muscle Oxygen Saturation

This is the first study to investigate the influence of CGs on muscle oxygen saturation at two locations simultaneously. In doing so, it is possible to report on specific oxygenation differences that are not detectable by a single NIRS measure or global oxygenation assessment. The pattern of muscle oxygen

saturation followed a similar pattern at both locations to those previously reported [105]. A rapid decrease in muscle oxygenation was observed following the onset of exercise, followed by a slow linear increase. However, in agreement with earlier studies [10,61], no differences between clothing conditions were observed in muscle oxygen saturation during exercise. During a 15.6 km trial run, Vercruyssen *et* al., [61] showed no effect of compression stockings on vastus lateralis oxygen saturation, however the NIRS probe was not positioned where compression was applied, therefore the authors could only conclude that compression stockings have no effect on systemic measures of muscle blood flow and oxygen saturation. Furthermore, Dascombe *et* al, [10] report no difference in vastus lateralis muscle oxygenation at running speeds of 12 and 14 $km \cdot h^{-1}$ when compression tights are worn, but do report an increased oxygen saturation at 10, 16 and 18 $km \cdot h^{-1}$. Several studies have reported positive effects of compression clothing on measures of muscle oxygen saturation [10,38,105], however these studies include heel-raise exercise [105] or measures are only obtained during rest periods [59]. Muscle oxygen saturation is determined by two predominant factors; the oxygen delivery rate and oxygen consumption. Measures of tHb obtained by NIRS provide a surrogate measure of tissue blood flow [249] and reflect changes to local blood volume. In the present study, compression tights did not alter total haemoglobin, indicating that muscle blood volume is unchanged at rest and during exercise between clothing conditions. However, obtaining NIRS measures during an arterial occlusion of the leg would provide a greater insight into muscle blood flow. It is not feasible to perform repeated arterial occlusions during exercise; therefore assessment of local oxygen delivery and consumption has previously been conducted immediately post-exercise, assuming the metabolic demand is the equivalent to the final stages of an exercise protocol [250]. Future investigations should implement an arterial occlusion protocol during brief rest intervals throughout steady state exercise to elucidate on flow and consumption changes with compression tights.

7.6.7 Running Kinematics

The present study was the first to investigate the influence of compression tights on running kinematics. Previous studies have included compression stockings only [81,84,94] or a combination of calf and thigh sleeves [160] and reported higher leg stiffness, lower contact time and lower stride length during constant rate running [84,160]. The present study revealed no differences in vertical oscillation, however in support of Kerherve *et al.,* [84], a shorter GCT was observed with compression. Cardiovascular parameters during submaximal running are affected by various factors, including running kinematics, such as vertical oscillation and GCT [251,252]. However, evidence appears equivocal regarding the association between GCT and RE, with several authors reporting either no relationship [253–255], improved RE with longer GCT [256] or improved RE with shorter contact time [257]. In the current study, a shorter GCT with compression tights caused no measurable change in RE. The change in contact time may be a result of decreased range of motion at the hip or knee joint, reducing stride length and contact time. Compression shorts decreased the range of motion (ROM) at the hip joint at rest, laying supine [75] and during a 60 m sprint [74]. Logically, decreases in ROM are only observed at the joints covered by the garment. By compression tights covering both the hip and knee joint, garments of this type offer the greatest opportunity to alter running gait. However, future research is required to explore whether decreases in ROM are observed at submaximal running speeds with compression tights.

No changes in mean vertical oscillation were revealed. However, there was substantial inter-individual variation in the metabolic response to compression that warrants further investigation. *Post hoc* analysis was conducted to determine if any characteristics of running mechanics may explain the individual response to compression tights. When participants are grouped according to changes in RE, those with the greatest improvement in RE had a lower overall vertical oscillation and vertical oscillation variability. A reduction in vertical oscillation and stride-to-stride variability may improve RE due to a lower vertical impulse and the body performing less work against gravity [258,259].

7.6.8 Interface Pressure Considerations

Target interface pressures were selected in accordance with recommendations associated with improved venous return [12], whereas garments pressures shown to influence running mechanics appear to be higher. Future investigations should assess the influence of compression tights on running economy applying an interface pressure of ~23 – 33 mmHg around the calf and ~20 mmHg around the thigh [84,160]. Fortunately, both studies used to inform this target threshold utilised the PicoPress pressure monitor, providing greater confidence in the precision of the pressure values proposed.

7.6.9 Limitations

The current study was designed to investigate the influence of compression tights at competition speed. However, in doing so, the participants running speed was determined from recent performances over 10 km, half- or full marathon. In Chapter 5 a relationship between the influence of compression tights and relative exercise intensity was reported. Yet, by asking participants to run at speeds associated with race performance of three varying distances, it is likely that the relative exercise intensity of participants was varied and possibly fell outside the previously observed range purported to respond positively to compression. Despite this, the current study confirms compression tights do not improve running economy at speeds associated with long distance races.

7.7 Conclusion

This study shows for the first time that wearing compression tights while running at speeds associated with competition pace reduces ground contact time. However, running economy, skin temperature, muscle oxygen saturation and vertical oscillation are not modified. There is evidence that the individual response to wearing compression tights varies greatly and could be associated with kinematic variables such as vertical oscillation. In order to explore the relationship between changes in running economy with compression tights and running gait parameters, future studies should select garments with interface pressures previously shown to alter running kinematics (~20 – 33 mmHg) rather than pressure thresholds that may influence blood flow (15 – 17 mmHg).

8 Summary

Lower limb graduated compression garments are an effective adjunct in the management of diseases of venous deficiency [89], with evidence to suggest that mechanically increasing transmural pressure causes a reduction in venous stasis, hypervolemia and cross-sectional vein diameter [96,260]. Since these early investigations, interest in the efficacy of sports compression garments has grown. Despite the number of sports compression studies, the absence of a common consensus of how to measure garment interface pressure limits the cross-study comparisons that can be made regarding garment performance. Establishing a preferred pressure measuring device and assessment method is crucial for the progression of sports compression literature. Chapter 3 investigated the criterion validity of portable devices capable of measuring interface pressure, identifying a suitable device for the subsequent intervention studies.

The literature review revealed few reproducible findings in support of acute performance improvement. The equivocal results previously reported may be linked to the heterogeneity of garments investigated [3,36,67,68]. It became evident that compression garments may produce small improvements in some performance measures (time to exhaustion [4]; 800 – 3000 m [69]) and physiological parameters (running economy [4]). Given the heterogeneity of the garments investigated, and the small yet notable improvement in running economy, it is plausible that factors such as garment type, interface pressure, exercise modality and exercise intensity influence the efficacy of CGs. This thesis focuses on the influence of compression tights, intentionally selecting a garment that covers the full leg musculature and the hip and knee joints. In doing so this provides the greatest opportunity for the garment to interact with various physiological systems (cardiovascular, haemodynamic, mechanacoreceptive and biomechanical). The influence of compression tights on running economy was investigated, exploring the effect of garment interface pressure in Chapter 4 and relative exercise intensity in Chapter 5. Chapter 7 explored the influence of compression tights on running economy at a competitive race speed. Within this investigation, a NIRS device validated in

Chapter 6 was used to monitor muscle oxygen saturation. The main findings of the thesis were as follows;

1) When compared with a medical reference standard, the PicoPress pneumatic pressure measuring device satisfied *a priori* thresholds at the posterior and lateral orientation with lower limb sports compression garments. Conversely, the Kikuhime did not satisfy thresholds for acceptable validity at any orientation, overestimating the pressure compared with a reference standard. These findings indicate that practitioners and researchers can confidently compare interface pressures obtained with the PicoPress against values reported with medical compression hosiery. The study also reports the physical properties of the compression tights used throughout this thesis (Chapter 3).
2) Correctly fitted compression tights applying a low level of interface pressure (ankle = 3.1 ± 1.3; calf =10.5 ± 3.1; thigh = 6.7 ± 0.6 mmHg) caused a small, *likely beneficial* improvement (95%:5%:0%; η^2 = 0.55) in running economy at 60% v$\dot{V}O_{2max}$. In contrast, oversized compression tights applying a lower level of interface pressure (ankle = 1.3 ± 0.9; calf = 9.1 ± 2.7; thigh = 3.8 ± 1.1 mmHg) did not improve running economy. These results indicate that compression tights applying a specific interface pressure produce a meaningful improvement in running economy of moderately trained individuals (Chapter 4).
3) The extent in which compression tights improve running economy is dependent on relative exercise intensity (r= -0.501, P<0.01). Expressed as caloric unit cost, running economy was improved by compression tights (d=0.93) at high relative exercise intensities (77.1-91.5% $\dot{V}O_{2max}$), whereas no effect was observed below this intensity range. This further elucidates the specific exercise conditions whereby compression tights might improve running economy (Chapter 5).
4) A recently developed low-cost NIRS device (MOXY) produced physiologically credible and comparable measures during rest and exercise against an established PortaMon system. The MOXY is most suited for individuals with a small adipose layer thickness (<7 mm) and when

the external pressure holding the device in place is below 20 mmHg. When these conditions are met, the MOXY produces reliable resting measures of muscle oxygen saturation (coefficient of variation = 5.7 - 6.2%). Furthermore, decreases in saturation during isometric exercise, arterial occlusion and dynamic arm crank exercise are strongly correlated between devices. The MOXY provides a lightweight option to monitor muscle oxygen saturation during dynamic exercise (Chapter 6).

5) Wearing compression tights decreases ground contact time (P = 0.03) but does not alter running economy (P = 0.91), SmO_2 (P = 0.15-0.84), vertical oscillation (P = 0.29), HR (P = 0.30) or skin temperature (P = 0.47-0.80) at a competitive race pace. It appears the individual response to compression tights is most improved in participants with a low vertical oscillation and exhibit less stride-to-stride variation in vertical oscillation (Chapter 7).

8.1 Empirical and practical implications of the findings

8.1.1 Measuring interface pressure with a portable pressure device

Reporting garment interface pressure is critical to enable comparative assessment of study findings. In order to further understand the bio-physical impact of interface pressure on physiological parameters and sports performance, optimal methods to measure *in vivo* pressure must be established. There are many measuring instruments (HOSY, PicoPress, Kikuhime, etc.) and methods (*in vivo*, assessment of fabric properties, etc.) that can be used to obtain the pressure profile of a compression garment. Despite guidelines published in 2006 alluding to a range of suitable portable pressure devices for *in vivo* assessment [34], the comparison of the PicoPress and Kikuhime device in this thesis is the first study to compare multiple portable devices with a medical reference standard (HOSY). Indeed, the concluding remarks of Hegarty *et al.,* [261] drew attention to this, stating that ‘future research must include the HOSY or other methods of measuring pressure. This will allow the point measurements from different devices to be matched and verified using an independent, continuous data-set, and correction factors’. Additionally, the authors suggest that ‘discrepancies between the predicted

pressures and on-body techniques need to be further studied. This should include testing at different points along the circumference of the limb with different sensor geometries.'

Chapter 3 found clear discrepancies between the interface pressures reported by two common devices. Analysis revealed the PicoPress is a suitable pneumatic pressure monitor, whereas the Kikuhime systemically overestimates interface pressure regardless of anatomical orientation. Interestingly, this investigation also revealed that the water-column method previously used to assess device accuracy and reproducibility [2] is insufficient at identifying systemic bias during *in vivo* assessments. Chapter 3 informs future research and international standardization, revealing a valid measurement device and assessment location(s). In light of the results, the PicoPress device was used throughout the thesis, featuring in all subsequent chapters.

8.1.2 The comparison of wireless NIRS devices

NIRS is a simple, non-invasive method for measuring the presence of oxygen in muscles and other tissues *in vivo* [262]. In Chapter 6, a recently developed low-cost NIRS device (MOXY) was compared against an established PortaMon system that makes use of the spatially resolved spectroscopy (SRS) algorithm, widely used in sports science and physiology research. The development of new NIRS device technology has taken near-infrared physiological monitoring out of the laboratory and into an applied sport setting. However, prior to widespread use, researchers and practitioner must be confident in the validity, reliability and accuracy of new technology. This is the first study to report the influence of increasing external pressure on measures of muscle oxygen saturation. Importantly, it was found that above a pressure threshold (>20 mmHg), the MOXY device reports lower SmO_2 values. It is likely that the MOXY is more sensitive to pressure-induced changes in the dermis and subcutaneous oxygenation and blood flow due to a smaller source:detector separation and the proprietary spatial resolution algorithm. This novel finding is the first to provide specific guidance regarding the application of the MOXY to minimise test-retest variation. Subsequent to the publication of Chapter 6, the manufacturers of the MOXY developed a 'light shield' capable of not only preventing unnecessary light from interfering with the measurements, but also providing a

means of controlling the pressure applied once attached to an individual. Furthermore, the investigation reports the test-retest reliability at rest and during isometric leg extension exercise of the MOXY and PortaMon device. This study is significant because the use of non-invasive methods to track and optimise training intensity, such as NIRS, is of increasing interest to coaches, athletes and scientists, yet data is lacking regarding the reliability of the MOXY device, nor has its performance been previously compared with alternative NIRS systems. Collectively, the results of Chapter 6 reveal the MOXY monitor is capable of producing valid measures of muscle oxygen saturation at rest and under a range of dynamic conditions. Given that the MOXY produces physiologically credible measures and is ~43% lighter than the PortaMon, the device was used in Chapter 7 as a means of measuring muscle oxygen saturation during submaximal running.

8.1.3 The influence of compression on running economy

The fundamental contribution of running economy to endurance running performance is widely acknowledged [238,246]. Strategies to enhance an athletes RE should be a primary objective for individuals who compete at distance running, including both moderately trained 'weekend warriors' and elite athletes alike. Current literature suggests that enhancing RE is achieved through the inclusion of 6-14 weeks of explosive strength and plyometric training [167,263], however contrary to popular belief, these findings are equivocal and highlight that such interventions are far from robust [263]. Chronic training interventions require time and the partial replacement of endurance training sessions. If acute strategies are capable of improving running economy, this would be of significant interest to athletes and coaches as they would require little to no time or replacement of training sessions in order to implement. Lower limb compression garments are an example of an acute strategy previously shown to cause small improvements in running economy [4,9,81,94]. However there was little evidence to indicate the specific garment type or applied interface pressures required to achieve meaningful improvements in RE. In Chapter 4, small, *likely beneficial* improvements in RE are reported with low-pressure sports compression tights, applying the greatest interface pressure at the calf. Additionally, it appears that tights must apply an interface pressure above a particular threshold

to elicit the observed improvement in RE. Previous studies have identified a dose response relationship with physiological [10,12] and kinematic variables [160], however this was the first study to find compression tights improved RE, while also reporting interface pressures obtained *in vivo*. Wearing non-graduated, low pressure (<15 mmHg) compression tights during submaximal running leads to an improved RE (+3.2%) at a relative intensity of ~80% $\dot{V}O_{2max}$.

Chapter 4 identified garment type, pressure gradient and associated interface pressures capable of improving RE. Chapter 5 demonstrated that the influence of compression tights on RE was dependant on relative exercise intensity. Furthermore, in this chapter, RE is reported as energy cost (caloric unit cost; $kcal \cdot kg^{-1} \cdot km^{-1}$), which accounts for substrate dependent variations in energy equivalent of a volume of oxygen [11]. This is the first study to reveal that CGs improve RE at high relative exercise intensities but not lower (</>77.7% $\dot{V}O_{2max}$), reporting a mean improvement of 2.8% between 77.7-91.5% $\dot{V}O_{2max}$.

During a marathon, participants perform at a speed equivalent to approximately 60 – 75% $\dot{V}O_{2max}$ [264]. Furthermore, recreational runners are reported to complete a half marathon at a relative exercise intensity between 75 - 85% $\dot{V}O_{2max}$ [164]. Perhaps the most practically relevant question of the thesis is whether compression tights can alter RE at competitive long distance race speeds which runners frequently train at. Despite increasing the interface pressure applied to the lower limbs in accordance with recommendations associated with improved venous function, no difference was reported in RE between clothing conditions (Chapter 7). It is plausible that moderately trained runners are already 'most' economical at race speed and therefore casts doubt on the usefulness of compression tights acutely benefiting an endurance runner. Chapter 7 represents the first study to investigate the influence of compression tights on running kinematics, revealing a shorter ground contact time during the final 3 min at competition speed. Furthermore, substantial inter-individual variation in running economy was observed with compression (ΔRE range -5.6 – 3.8%), indicating that individuals who possess a lower overall vertical oscillation and stride-to-stride variability may benefit from compression tights. Throughout chapters 4, 5 and 7 the typical improvement in RE with compression tights is between 2 –

4%. Acute interventions that potentially augment RE are important, as small changes in RE are associated with improvements in running performance [246]. Nevertheless, intra-individual variation of RE ranges between 1.9-3.1% in well controlled studies using moderately trained participants [166,265]. Only when changes in running economy exceed the typical error can we confidently interpret a meaningful change [177]. The thesis reveals that only in specific garment and exercise intensity conditions can compression tights improve RE. However, the magnitude of this improvement is likely to be small. In addition, the improvements in RE are likely to only be observed at unfamiliar running speeds. Pereira *et al.,* [166] stated that optimum stride length is easier to identify and more consistent at a familiar speeds. Indeed, Chapter 7 confirms that compression tights produce no improvement in RE when participants ran a competitive race pace.

8.2 Limitations

A number of limitations within the present work must be acknowledged. Chapter 3 compares two portable pressure monitors with a medical reference standard. The comparisons made throughout this investigation were focused on the garment pressure applied at the calf. It is unknown how the devices perform at any other location such as the ankle or thigh. Thomas [133] revealed that sensor accuracy of both the PicoPress and Kikuhime are proportional to the circumference of the cylinder to which it is applied. At smaller circumferences, the portable devices overestimate the pressure applied, due to the sensors undergoing greater deformity to conform to the curvature. In light of this, it is expected that ankle interface pressure obtained by the PicoPress and Kikuhime will be higher than that reported by the HOSY. Conversely, measures at the thigh location should align closer with values obtained using a medical reference standard due to the larger circumference.

Throughout the thesis the same type of compression garment has be investigated (SKINS, A400 long tights). Lee *et al.,* [266] found that subtle changes to the level of interface pressure and fabric composition were capable of influencing the kinematics and kinetics during drop jump landing. Given that biomechanical responses are garment specific, extrapolating the current results across alternative

compression garments should be conducted with caution. Furthermore, the compression tights in the thesis delivered non-graduated pressure, with the highest interface pressure recorded at the calf. The medical compression literature clearly indicates that graduated compression is required to have the greatest benefit on minimising venous stasis and increasing venous blood flow velocity. It is plausible that graduated compression may influence haemodynamic parameters to a greater extent than non-graduated during exercise. Sports compression garments often apply low interface pressures at the ankle, increasing upwards and peaking at the maximum calf girth [36]. This is most likely a commercial decision driven by consumer demand for garment comfort and ease of donning.

Chapter 5 reveals the influence of compression tights on running economy varies by relative exercise intensity. This finding was established by analysing the participants RE response at a speed equivalent to 60-65% v$\dot{V}O_{2max.}$ Retrospective analysis revealed the reported relationship between exercise intensity and RE response. In this instance, data was not obtained by implementing a repeated measures design, requiring participants to run at multiple relative exercise intensities i.e. 60, 70, 80 and 90% $\dot{V}O_{2max.}$ By conducting a research design in this manner, it will be possible to elucidate the present findings.

In Chapter 7 the individual response to wearing compression tights when running at a competitive race speed varied greatly, yet when analysed as a group, no improvement in RE was observed. It is possible that the individual response was related to the relative exercise. However, it was not possible to explore this relationship as participants did not complete a preliminary $\dot{V}O_{2max}$ assessment to establish relative $\dot{V}O_2$ uptake.

8.3 Future research directions

A vast majority of the sports compression literature has been conducted with male participants. Chapter 7 revealed that changes in RE among female participants (n=4) was greater than previously reported intra-individual RE variation. However, this observation lacks statistical power and future

research should look to investigate the female response to compression tights with an adequately powered study. This is particularly relevant due to sex differences in lower extremity mechanics during running [122].

Lower limb compression garments applying an interface pressure between 20 – 30 mmHg change running gait variables to a greater extent than those with lower pressures [160]. Chapter 7 reveals a possible interaction between running kinematics and RE economy changes with compression. This raises the question whether compression tights with a higher interface pressure (20 – 30 mmHg) would produce a greater improvement in RE than that observed in the thesis. To achieve these pressures, it is recommended that single layer garments are identified rather than layering garments on top of one another as was performed in Chapter 7. This would minimise the additional garment weight thought to possibly hinder the ergogenic potential of compression on running mechanics.

8.4 Conclusion

The work contained in this thesis has progressed three distinct areas.

(1) The PicoPress provides a valid measure of interface pressure at the posterior and lateral location of the calf. This finding contributes towards international standardization by identifying a portable pressure sensor and assessment location capable of replicating pressure values established from a reference standard. This is an important finding given the low-cost and speed in which garment pressure can be determined using a portable pressure monitor when compared with indirect methods.

(2) The MOXY and PortaMon NIRS devices produce physiologically credible measures of muscle oxygen saturation during supine rest and demonstrate a similar trend during dynamic exercise. However, the use of the MOXY device should be limited to individuals with a low adipose tissue thickness and the external pressure applied to hold the device in place is either standardised upon each application or kept below 20 mmHg.

(3) Sports compression tights produce small improvements in RE when garments are correctly fitted, apply a low level of interface pressure and relative exercise intensity is high. The benefits of

compression appear diminished when participants run at a competitive race pace and therefore it is questionable to what extent compression tights can meaningfully contribute toward improved RE and ultimately better endurance running performance.

9 References

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10 Appendices

Appendix 1: University of Essex institutional ethical review board approval

University of Essex

Updated application + consent form provided.
31.9.17.

Application for Ethical Approval of Research Involving Human Participants

This application form must be completed for any research involving human participants conducted in or by the University. 'Human participants' are defined as including living human beings, human beings who have recently died (cadavers, human remains and body parts), embryos and foetuses, human tissue and bodily fluids, and human data and records (such as, but not restricted to medical, genetic, financial, personnel, criminal or administrative records and test results including scholastic achievements). Research must not commence until written approval has been received (from departmental Director of Research/Ethics Officer, Faculty Ethics Sub-Committee (ESC) or the University's Ethics Committee). This should be borne in mind when setting a start date for the project. Ethical approval cannot be granted retrospectively and failure to obtain ethical approval prior to data collection will mean that these data cannot be used.

Applications must be made on this form, and submitted electronically, to your departmental Director of Research/Ethics Officer. A signed copy of the form should also be submitted. Applications will be assessed by the Director of Research/Ethics Officer in the first instance, and may then passed to the ESC, and then to the University's Ethics Committee. A copy of your research proposal and any necessary supporting documentation (e.g. consent form, recruiting materials, etc) should also be attached to this form.

A full copy of the signed application will be retained by the department/school for 6 years following completion of the project. The signed application form cover sheet (two pages) will be sent to the Research Governance and Planning Manager in the REO as Secretary of the University's Ethics Committee.

1. Title of project: **The influence of lower body compression garments on physiological and performance parameters during sub-maximal running.**

2. The title of your project will be published in the minutes of the University Ethics Committee. If you object, then a reference number will be used in place of the title.
   Do you object to the title of your project being published? Yes ☐ / No ☒

3. This Project is: ☒ Staff Research Project ☐ Student Project

4. Principal Investigator(s) (students should also include the name of their supervisor):

Name:	Department:
Chris McManus	**School of Sport Rehab and Exercise Science**
Josh Butson	School of Sport Rehab and Exercise Science

5. **Proposed start date**: 01/09/17

6. **Probable duration**: 4 weeks

7. Will this project be externally funded? Yes ☐ / No ☒
   If Yes,

8. What is the source of the funding?

9. If external approval for this research has been given, then only this cover sheet needs to be submitted
   External ethics approval obtained (attach evidence of approval) Yes ☐/ No ☐

Declaration of Principal Investigator:

The information contained in this application, including any accompanying information, is, to the best of my knowledge, complete and correct. I/we have read the University's *Guidelines for Ethical Approval of Research Involving Human Participants* and accept responsibility for the conduct of the procedures set out in this application in accordance with the guidelines, the University's *Statement on Safeguarding Good Scientific Practice* and any other conditions laid down by the University's Ethics Committee. I/we have attempted to identify all risks related to the research that may arise in conducting this research and acknowledge my/our obligations and the rights of the participants.

Signature(s): .....

Name(s) in block capitals: ....CHRIS MCMANUS.....

Date: ...16/08/2017.....

Supervisor's recommendation (Student Projects only):

I have read and approved the quality of both the research proposal and this application.

Supervisor's signature: .....

Outcome:

The departmental Director of Research (DoR) / Ethics Officer (EO) has reviewed this project and considers the methodological/technical aspects of the proposal to be appropriate to the tasks proposed. The DoR / EO considers that the investigator(s) has/have the necessary qualifications, experience and facilities to conduct the research set out in this application, and to deal with any emergencies and contingencies that may arise.

This application falls under Annex B and is approved on behalf of the ESC ☑
This application is referred to the ESC because it does not fall under Annex B ☐
This application is referred to the ESC because it requires independent scrutiny ☐

Signature(s): .....

Name(s) in block capitals: J. Mills

Department: SRES

Date: 14/09/2017

The application has been approved by the ESC ☐
The application has not been approved by the ESC ☐
The application is referred to the University Ethics Committee ☐

Signature(s): .....

Name(s) in block capitals: .....

Faculty: .....

Date: .....

Appendix 2: Participant information packs (Chapters 3 – 7)

Participant Information Sheet

What is the purpose of this study?

This study aims to compare two hand-held devices which measure the pressure applied by compression garments.

How will the study be conducted?

The research will require you to attend the Human Performance Unit once for no longer than 30 minutes. After some basic measurements (calf circumference) you will be asked to wear two compression socks and two compression tights. The pressure applied by these garments on the front, back and side of your calf will be measured. No exercise is required. Please wear shorts to the testing session.

Where will the research take place?

At the Human Performance Unit located in the Centre for Sport and Exercise Science, University of Essex, Wivenhoe Park, Colchester, Essex CO4 3SQ.

By taking part in this study, please be aware that:

- *I am free to withdraw from the study at any time without giving reason and without penalty*
- *All information collected during this research will remain anonymous*
- *The person in control of the test will explain the nature and purpose of the test and will inform me of any foreseeable risk to my health as a result of my participation*

Do I have to take part?

No, it is your choice whether or not to take part. Please talk to others about the study if you wish and ask us if anything is not clear. If you decide to take part, you can leave the study at any time without giving a reason.

What will happen to me if I take part?

When you are recruited you will be shown some of the equipment that will be used during your participation. You will be able to ask any questions that you may have at this point before deciding you are interested in taking part.

Will I be paid for my participation?

You will not be paid for taking part in this study.

Why might you be not able to take part in the study?
If you have a history of venous insufficiency, heart disease (including irregular heartbeats), high blood pressure, problems with the nervous system or taking medicine that alters the cardiovascular system or the nervous system you will not be able to participate. In addition, if you have any muscle or joint problems that prevent you from standing for a prolonged period (60 minutes) we ask that you do not take part.

What if relevant new information becomes available?

If additional information becomes available during the course of the research, it will mainly be conveyed in the form of e-mail. E-mail or text messages will be used for reminders for you depending on your preference.

What will happen if I don't want to carry on with the study?

If you decide to take part, you can still leave the study at any time without giving a reason. Identifiable data already collected with consent would be retained and used in the study. No further data would be collected or any other research procedures carried out on or in relation to you.

Who is organising the research?

The University of Essex is organising this study. The research team are employees and students of the University of Essex. The principle investigator is Mr Chris McManus (details below). Other members of the research team include undergraduate students from the School of Sport, Rehabilitation and Exercise Sciences.

Will my taking part in this study be kept confidential?

If you decide to take part in this study, any information collected about you as part of this project will remain confidential and your identity will not be revealed outside the research team. Hardcopy data will be digitized within four weeks of collection. Once digitized, hardcopy data will be destroyed by the principle investigator. Digitized data will be stored on password protected computers and on a GDPR approved EU cloud-based repository. The dataset will be stored on a password protected computer; only accessible by the named investigators. No personally identifiable data/markers (name, address, email address etc.) will be recorded on the same digitized dataset.

A separate, password protected file, that links your name, address and email address to the identifier code will be kept, enabling us to contact you for future reassessments. This file will be password protected, securely stored on a password protected computer, on a password protected GDPR approved EU cloud-based repository.

Anonymous, digitized data will be stored indefinitely on the approved cloud repository as the results will contribute toward an ongoing analysis of health and performance changes of University students.

What will happen to the results of this study?

Any information collected about you will only be used for the purposes of this project. The anonymous results may be published in scientific journals, undergraduate reports and used for teaching. You will not be personally identified in any report or publication. You can request a copy of the findings. You will also be given individual feedback after completion of the study.

What if there is a problem or you are unhappy with the conduct of this study?

If you have any concerns about any aspect of the study or you have a complaint, in the first instance please contact the principal investigator of the project Chris McManus (contact details below). If are still concerned or you think your complaint has not been addressed to your satisfaction, please contact the Director of Research in the principal investigator's department (Dr Matthew Taylor, tel 01206 872818; email mtaylor@essex.ac.uk) , If you are still not satisfied, please contact the University's Research Governance and Planning Manager, Sarah Manning-Press, Research and Enterprise Office (tel 01206 87-3561; e-mail sarahm@essex.ac.uk). In the event that something does go wrong and you are harmed

during the research and this is due to someone being at fault, you may have grounds for a legal action for compensation but you may have to pay your legal costs.

Ethical Approval
This project has been reviewed on behalf of the Science and Health Ethics Sub-Committee and has been given approval.

For further information about this project please contact
Mr Chris McManus,
University of Essex
Telephone: 01206 874475
e-mail cmcman@essex.ac.uk

If you do decide to take part, you will be given a copy of this information sheet to keep and will be asked to sign a consent form.

Thank you for taking time to read this Participant Information Sheet.

University of Essex

HUMAN PERFORMANCE UNIT

Participants Wanted For Research Opportunity

'The influence of lower body clothing on run performance'

Are you...?

- Male
- Aged 18 or over
- Physically active / Runner
- Typically completing at least 2 training sessions per week

Number of Visits:

You will be required to attend the University of Essex for 4 visits. Visit duration will last approximately 60-90 min. The table below outlines the possible dates for participation.

Visit 1	Visit 2	Visit 3	Visit 4
Monday 5th January	Thursday 8th January	Monday 12th January	Thursday 15th January

Timings can be discussed and arranged around your schedule; however, all visits must occur at the same time of day.

Visit 1: Preliminary visit = VO2max run test and familiarisation with vertical jump platform

Visit 2, 3, 4: Intervention testing ((1) Clothing garment 1 (compression), (2) Clothing garment 2 (compression), (3) Clothing garment 3 (running shorts)

Protocol:

Upon arrival your height and weight will be recorded to ascertain the correct size compression garment. Following this, 6 anatomical landmarks will be marked with a small washable pen on your lower leg (alcohol swabs will be provided to wipe pen off). The level of compression will be measured using a small inflatable bladder between your skins surface and the compression garment.

Following this, you will undertake the following protocol;

1) Vertical jump test (5 repeated vertical jumps)

2) 15 minute run at 80% VO2max

3) Vertical jump test (5 repeated vertical jumps)

4) Test to exhaustion at peak running speed (velocity that corresponds to VO2max)

You are asked to record your food consumption and activities during the 24 hours prior to your first visit. Following this, you are requested to repeat the same food consumption and activities protocol before all remaining tests. Additional documentation and information will be provided to aid with this.

Do not exercise 24 hours before test, we require you to be rested for the test. Do no 'hard' training or competition for 48 hours before.

It is imperative that you do not consume alcohol, caffeine or beetroot juice 12 hours before each trial. This includes tea, coffee, decaf coffee, energy drinks containing caffeine, medication containing caffeine or any other caffeine containing products.

What feedback do I get and can I have my results?

Upon completion of the 4 visits you can request feedback regarding your performance and data associated with this. Data that is of likely interest includes;

- Your response to the intervention measured
- VO2max (Maximum oxygen uptake)
- Max heart rate
- Running economy
- Time to exhaustion performance results (All 3)
- Debrief outlining intervention differences

Do I have to take part?

It is up to you to decide whether or not to take part. If you decide to take part you will be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason.

What if something goes wrong?

If you wish to complain or have any concerns about any aspect of the way you have been approached or treated during the course of this study, please contact Dr Dave Parry, Director of the Human Performance Unit, University of Essex, Wivenhoe Park, CO43SQ, Essex.

Will my taking part in this study be kept confidential?

All information which is collected about you during the course of the research will be kept strictly confidential so that only the researcher carrying out the research will have access to such information. All data will be stored on a personal computer and backed up to a safe storage device and stored in a locked office.

Who may I contact for further information?

If you would like more information about the research before you decide whether or not you would be willing to take part, please contact:

Chris McManus at the Human Performance Unit, University of Essex, Wivenhoe, Essex, CO4 3SQ.

Email: cmcman@essex.ac.uk

Phone: 01206 874475

University of Essex

HUMAN PERFORMANCE UNIT

‘The influence of lower body clothing on sub-maximal running’

Are you...?

- Male
- Aged 18 or over
- Physically active / Runner
- Typically completing at least 2 training sessions per week
- Currently uninjured and without lower limb injury for 4 weeks
- Without illness or circulatory complaints of the lower limbs

Number of Visits:

You will be required to attend the University of Essex for 3 visits. Visit duration will last approximately 45 min for VISIT 1 and 90 min for VISIT 2 and 3. The table below outlines the possible dates for participation.

	Date	Date	Date	Date	
Visit 1 (Maximal Run Test)	**Tuesday 28th July**	**Wednesday 29th July**	**Thursday 30th July**	**Friday 31st July**	← *Select 1 date from this row*
Visit 2 (Experimental Trial)	**Monday 3rd August**	**Tuesday 4th August**	**Thursday 6th August**	**Friday 7th August**	← *Select 1 date from this row*
Visit 3 (Experimental Trial)	**Monday 10th August**	**Tuesday 11th August**	**Thursday 13th August**	**Friday 14th August**	← *Select 1 date from this row*

Time Availabilities for Visit 2 + 3:

- 9:00 – 10:30
- 11:00 – 12:30
- 13:00 – 14:30
- 15:00 – 16:30
- 17:00 – 18:30

- Timings can be discussed and arranged around your schedule for Visit 1; however, both visits 2 + 3 must occur at the same time of day. Please contact us to discuss this.

Visit 1: Preliminary visit = VO2max run test (7-15 minutes) and familiarisation with running at designated sub-maximal intensity (5 minutes)

Visit 2 + 3: Intervention testing (1) Clothing garment 1 (compression), (2) Clothing garment 2 (running shorts)

Protocol:

Visit 1: Upon arrival a physical activity readiness questionnaire and consent form will be provided to you and a researcher will discuss the protocol verbally. Subsequently, height and weight will be recorded, prior to undertaking a warm-up on the treadmill of 5-10 minutes. Prior to beginning the maximal test to exhaustion, a mask will be fitted to your face to allow collection of respiratory gases. The treadmill will begin at a low-moderate intensity and progressively increasing in speed and incline until a point of volitional fatigue. After a rest period, the treadmill will be set at 60% of the speed achieved during the maximum test to act as a familiarisation session (and cool-down) for 5-10 minutes.

Visit 2+ 3: 6 anatomical landmarks will be marked with a small washable pen on your lower leg (alcohol swabs will be provided to wipe pen off) when undertaking the compression trial. The level of compression will be measured using a small inflatable bladder between your skins surface and the compression garment.

Following this, you will undertake the following protocol;

1) 20 minute run at 60% VO2max

2) 60 minute recovery period with blood lactate measures at 0, 5, 10, 15, 30 and 60 minutes *(you are requested to remain seated throughout this period. We can provide laptop / internet access to assist with occupying time)*

- You are asked to record your food consumption and activities during the 24 hours prior to your first visit. Following this, you are requested to repeat the same food consumption and activities protocol before all remaining tests. Additional documentation and information will be provided to aid with this.

- Do not exercise 24 hours before test, we require you to be completely rested for the test. Do no 'hard' training or competition for 48 hours before.

- It is imperative that you do not consume alcohol, caffeine or beetroot juice 12 hours before each trial. This includes tea, coffee, decaf coffee, energy drinks containing caffeine, medication containing caffeine or any other caffeine containing products. Furthermore, no food should be consumed in the 3 hours prior to visiting the University.

What feedback do I get and can I have my results?

Upon completion of the 3 visits you can request feedback regarding your performance and data associated with this. Data that is of likely interest includes;

- Your response to the intervention measured
- VO2max (Maximum oxygen uptake)
- Max heart rate
- Running economy
- Debrief outlining intervention differences

Do I have to take part?

It is up to you to decide whether or not to take part. If you decide to take part you will be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason.

What if something goes wrong?

If you wish to complain or have any concerns about any aspect of the way you have been approached or treated during the course of this study, please contact Dr Dave Parry, Director of the Human Performance Unit, University of Essex, Wivenhoe Park, CO43SQ, Essex.

Will my taking part in this study be kept confidential?

All information which is collected about you during the course of the research will be kept strictly confidential so that only the researcher(s) carrying out the research will have access to such information. All data will be stored on a personal computer and backed up to a safe storage device and stored in a locked office.

Who may I contact for further information?

If you would like more information about the research before you decide whether or not you would be willing to take part, please contact:

Chris McManus at the Human Performance Unit, University of Essex, Wivenhoe, Essex, CO4 3SQ.

Email: cmcman@essex.ac.uk

Phone: 01206 873290 or 01206 874475

University of Essex

Department of Biological Sciences
Wivenhoe_Park
Colchester CO4 3SQ
Telephone: 01206 873333
Facsimile: 01206 872592
URL:http://www.essex.ac.uk/

January 2015

Study Title: Assessment of the inter-day reliability of a wireless near-infrared spectroscopy device during rest and exercise

Dear Participant,

We would like to take this opportunity to invite you to participate in a research project which will take place during Monday 26th January – Friday 27th February 2015. Before you decide, we would like you to understand why the research is being done and what it would involve for you. Part 1 of this Participant Information Sheet tells you why we are doing this research and what will happen to you if you take part. Part 2 gives you more details about how the study will be conducted.

Background to this research

The aim of the project is to assess the inter-reliability of two different muscle oxygen saturation devices: (1) Portamon and (2) Moxy at rest and during a repeat isometric quadriceps contraction test and compare these values between devices. Muscle oxygen saturation and haemoglobin variables will be measured non-invasively by a wireless optical device that is attached to the participant's leg.

PART 1 OF THE INFORMATION SHEET

How have I been selected?

You have been invited to take part in this study because you are student of the Colne Rugby Academy and you have indicated that you are happy to participate in the study.

Do I have to take part?

No, it is your choice whether or not to take part. Please talk to others about the study if you wish and ask us if anything is not clear. If you decide to take part, you can leave the study at any time without giving a reason.

What will happen to me if I take part?

When you are recruited you will be shown some of the equipment that will be used during you participation. You will be able to ask any questions that you may have at this point before deciding you are interested in taking part.

What will I have to do?

The study involves five visits to The University biomechanics lab. Firstly, to measure your height, weight and lower limb skin fold thickness and to familiarise you with the data collection procedures for the exercise testing on your second visit. The first visit will also involve an assessment of maximal quadriceps voluntary contraction (MVC) upon an isokinetic dynamometer. This first visit should take no longer than 30 minutes.

The remaining four visits will take no longer than 30 minutes each. You will be required to perform two thirty second isometric holds at 30 and 50% MVC, while blood oxygen saturation of your leg muscle will be measured using a non-invasive portable device. The blood oxygenation test is a completely painless test that uses near infrared light to detect changes in muscle oxygenation in the tissue.

You will be asked to follow some simple rules prior to attending for your testing:

1. No intense physical exercise for 24 hours before visits
2. No alcohol or caffeine for 24 hours before the test
3. No heavy meal in the last 4 hours before test (have some breakfast with a drink)

How will we contact you about visits?

We will ask you your preferred method of communication such as e-mail to remind you about your visits.

Will I be paid for my participation?

You will not be paid for taking part in this study.

Why might you be not able to take part in the study?

If you have a history of heart disease (including irregular heartbeats), high blood pressure, problems with the nervous system or taking medicine that alters the cardiovascular system or the nervous system you will not be able to participate. In addition, if you any lower limb muscle or joint problems you will not be able to participate in the study.

What if there is a problem?

Any complaint about the way you have been dealt with during the study or any possible harm you might suffer will be addressed. The detailed information on this is given in Part 2 of this sheet.

Will my taking part in the study be kept confidential?

We will follow ethical and legal practice and all information about you will be handled in confidence. The details are included in Part 2.

This completes Part 1. If the information in Part 1 has interested you and you may want to join the study, please read the additional information in Part 2 before making any decision.

PART 2 OF THE INFORMATION SHEET

What if relevant new information becomes available?

If additional information becomes available during the course of the research, it will mainly be conveyed in the form of e-mail or by letters if you have no access to e-mail (through internal post). E-mail or text messages will be used for reminders for you depending on your preference.

What will happen if I don't want to carry on with the study?

If you decide to take part, you can still leave the study at any time without giving a reason. Identifiable data already collected with consent would be retained and used in the study. No further data would be collected or any other research procedures carried out on or in relation to you.

Who is organising and funding the research?

The University of Essex is organising this study. The research team are employees of the University of Essex.

What if there is a problem or you are unhappy with the conduct of this study?

If you have any concerns or issues with the study please speak to Chris McManus in the first instance, unless you feel it more appropriate to speak to the Head of the Department of Biological Sciences (tel 01206 87-3337; e-mail craines@essex.ac.uk), or to Sarah Manning-Press, Research Governance and Planning Manager, Research and Enterprise Office (tel 01206 87-3561; e-mail sarahm@essex.ac.uk). In the event that something does go wrong and you are harmed during the research and this is due to someone being at fault, you may have grounds for a legal action for compensation but you may have to pay your legal costs.

All research is looked at by independent group of people, called a Research Ethics Committee, to protect your interests.

If you do decide to take part, you will be given a copy of this information sheet to keep, and will be asked to sign a consent form.

Will my taking part in this study be kept confidential?

If you decide to take part in this study, any information collected about you as part of this project will remain confidential and your identity will not be revealed outside the research and medical team. Any information about you which is collected will have your name and address removed so that you cannot be recognised. Information may be looked at by regulatory authorities to check that the study is being carried out correctly. However, your name and address will not be disclosed as your identity will be allocated a code and in this way will remain anonymous. Data will be handled, processed and stored in accordance with the Data Protection Act 1998 http://www.opsi.gov.uk/acts/acts1998/ukpga_19980029_en_1

What will happen to the results of this study?

Any information collected about you will only be used for the purposes of this project and will be disposed of securely when research is complete. The results may be published in scientific journals, undergraduate reports and used in presentations to healthcare and other interested parties. You will not be personally identified in any report or publication. You can request a copy of the findings. You will also be given individual feedback after completion of the study. This is NOT a clinical diagnosis.

What will happen to any samples I give?

The blood samples you give will be analysed within 24 hours to investigate blood lactate levels. After this analysis the samples will be destroyed and will not be used for any other research. Prior to disposal, samples will be stored with no personal details on them just a participant number.

For further information about this project please contact
Chris McManus at the University of Essex (Telephone: 07787259096, e-mail cmcman@essex.ac.uk)

Thank you for taking time to read this Participant Information Sheet.

University of Essex

University of Essex

Department of Biological Sciences Wivenhoe_Park
Colchester CO4 3SQ
Telephone: 01206 873333
Facsimile: 01206 872592
URL:http://www.essex.ac.uk/

August 2017

Study Title: Performance comparison of the MOXY and PortaMon near-infrared spectroscopy muscle oxygenation monitors during dynamic arm-crank exercise

Dear Participant,

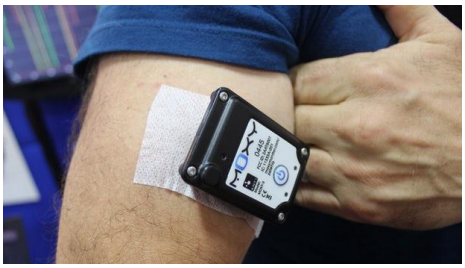
We would like to take this opportunity to invite you to participate in a research project which will take place during August 2017 – September 2017. Before you decide, we would like you to understand why the research is being done and what it would involve for you. Part 1 of this Participant Information Sheet tells you why we are doing this research and what will happen to you if you take part. Part 2 gives you more details about how the study will be conducted.

Background to this research

The aim of the project is to assess two different muscle oxygen saturation devices: (1) Portamon and (2) MOXY at rest and during an incremental arm crank exercise and compare these values between devices. Furthermore, we wish to investigate the devices when blood flow to the muscle being assessed is stopped (via an occlusion). Muscle oxygen saturation and haemoglobin variables will be measured non-invasively by a wireless optical device that is attached to the participant's leg.

Portamon Device

MOXY Device



PART 1 OF THE INFORMATION SHEET

How have I been selected?

You have been invited to take part in this study because you have responded to an advert, email or alternative form of communication.

Do I have to take part?

No, it is your choice whether or not to take part. Please talk to others about the study if you wish and ask us if anything is not clear. If you decide to take part, you can leave the study at any time without giving a reason.

What will happen to me if I take part?

When you are recruited you will be shown some of the equipment that will be used during you participation. You will be able to ask any questions that you may have at this point before deciding you are interested in taking part.

What will I have to do?

The study involves two visits to The University, Clinical Physiology Lab. Firstly, to measure your height, weight and bicep skinfold thickness and to undertake an incremental arm crank exercise followed by a 5 minute period of blood flow occlusion to your dominant arm.

The second visit will be a repeat of the first; however, an alternative device will be placed on your bicep to that used in the first visit.. The measure of muscle oxygenation is a completely painless process that uses near infrared light to detect changes in muscle oxygenation in the tissue.

The arm crank exercise will cause some mild feeling of discomfort that is typically associated with maximal exercise to exhaustion.

The blood flow occlusion may also cause discomfort, tingling feeling in the arm and a sensation of numbness. These feelings quickly return to normal upon releasing the cuff.

You will be asked to follow some simple rules prior to attending for your testing:

1. No intense physical exercise for 24 hours before visits
2. No alcohol or caffeine for 12 hours before the test
3. No food consumed in the last 2 hours before test

How will we contact you about visits?

We will ask you your preferred method of communication such as e-mail to remind you about your visits.

Will I be paid for my participation?

You will not be paid for taking part in this study.

Why might you be not able to take part in the study?

If you have a history of heart disease (including irregular heartbeats), high blood pressure, problems with the nervous system or taking medicine that alters the cardiovascular system or the nervous system you will not be able to participate. In addition, if you any lower limb muscle or joint problems you will not be able to participate in the study.

What if there is a problem?

Any complaint about the way you have been dealt with during the study or any possible harm you might suffer will be addressed. The detailed information on this is given in Part 2 of this sheet.

Will my taking part in the study be kept confidential?

We will follow ethical and legal practice and all information about you will be handled in confidence. The details are included in Part 2.

This completes Part 1. If the information in Part 1 has interested you and you may want to join the study, please read the additional information in Part 2 before making any decision.

PART 2 OF THE INFORMATION SHEET

What if relevant new information becomes available?

If additional information becomes available during the course of the research, it will mainly be conveyed in the form of e-mail. E-mail or text messages will be used for reminders for you depending on your preference.

What will happen if I don't want to carry on with the study?

If you decide to take part, you can still leave the study at any time without giving a reason. Identifiable data already collected with consent would be retained and used in the study. No further data would be collected or any other research procedures carried out on or in relation to you.

Who is organising and funding the research?

The University of Essex is organising this study. The research team are employees of the University of Essex.

What if there is a problem or you are unhappy with the conduct of this study?

If you have any concerns or issues with the study please speak to Chris McManus in the first instance, unless you feel it more appropriate to speak to Sarah Mumford, School Manager for the School of Sport, Rehabilitation and Exercise Science (tel 01206 87-3348; e-mail smumfo@essex.ac.uk), or to Sarah Manning-Press, Research Governance and Planning Manager, Research and Enterprise Office (tel 01206 87-3561; e-mail sarahm@essex.ac.uk). In the event that something does go wrong and you are harmed during the research and this is due to someone being at fault, you may have grounds for a legal action for compensation but you may have to pay your legal costs.

All research is looked at by independent group of people, called a Research Ethics Committee, to protect your interests.

If you do decide to take part, you will be given a copy of this information sheet to keep, and will be asked to sign a consent form.

Will my taking part in this study be kept confidential?

If you decide to take part in this study, any information collected about you as part of this project will remain confidential and your identity will not be revealed outside the research and medical team. Any information about you which is collected will have your name and address removed so that you cannot be recognised. Information may be looked at by regulatory authorities to check that the study is being carried out correctly. However, your name and address will not be disclosed as your identity will be allocated a code and in this way will remain anonymous. Data will be handled, processed and stored in accordance with the Data Protection Act 1998 http://www.opsi.gov.uk/acts/acts1998/ukpga_19980029_en_1

What will happen to the results of this study?

Any information collected about you will only be used for the purposes of this project and will be disposed of securely when research is complete. The results may be published in scientific journals, undergraduate reports and used in presentations to healthcare and other interested parties. You will not be personally identified in any report or publication. You can request a copy of the findings. You will also be given individual feedback after completion of the study. This is NOT a clinical diagnosis.

For further information about this project please contact
Chris McManus at the University of Essex (Telephone: 01206 874475, e-mail cmcman@essex.ac.uk)

Thank you for taking time to read this Participant Information Sheet.

University of Essex

School of Sport, Rehabilitation and Exercise Sciences Wivenhoe Park
Colchester CO4 3SQ
Telephone: 01206 873348
URL:http://www.essex.ac.uk/

August 2017

Study Title: The influence of lower body compression garments on physiological and performance parameters during sub-maximal running.

Dear Participant,

We would like to take this opportunity to invite you to participate in a research project which will take place during August 2017 – October 2017. Before you decide, we would like you to understand why the research is being done and what it would involve for you. Part 1 of this Participant Information Sheet tells you why we are doing this research and what will happen to you if you take part. Part 2 gives you more details about how the study will be conducted.

Background to this research

Compression garments worn on the lower body have been shown to elicit various physiological responses in relation to exercise performance. The aim of this study is to further interrogate previous findings and explore the influence of lower body compression garments on running performance. This includes physiological measures such as skin temperature, heart rate, muscle oxygenation and respiratory gas data.

PART 1 OF THE INFORMATION SHEET

How have I been selected?
You have been invited to take part in this study because you have responded to an advert, email or alternative form of communication.

Do I have to take part?
No, it is your choice whether or not to take part. Please talk to others about the study if you wish and ask us if anything is not clear. If you decide to take part, you can leave the study at any time without giving a reason.

What will happen to me if I take part?
When you are recruited you will be shown some of the equipment that will be used during you participation. You will be able to ask any questions that you may have at this point before deciding you are interested in taking part.

What will I have to do?

The study involves a single visit to The University, Human Performance Unit Lab. Firstly your height, weight will be taken as well as skinfold thickness of your gastrocnemius and vastus lateralis. Muscle oxygen devices (MOXY) will be attached at these locations using tape and a light strapping. The measure of muscle oxygenation is a completely painless process that uses near infrared light to detect changes in muscle oxygenation in the tissue. Participants will be required to shave a small patch of skin where the MOXY device will be placed. You will also be required to have a skin temperature probe at these locations, wear a mask for gas data and a heart rate strap.

University of Essex

School of Sport, Rehabilitation and Exercise Sciences Wivenhoe Park
Colchester CO4 3SQ
Telephone: 01206 873348
URL:http://www.essex.ac.uk/

For the running you will be require to complete 2 x 15 minute sub-maximal runs with a 30 minute rest period in between whereby you will wear plain running clothes for one, and lower body compression tights for the other.

You will be asked to follow some simple rules prior to attending for your testing:

1. No intense physical exercise for 24 hours before visits
2. No alcohol or caffeine for 24 hours before the test
3. No heavy meal in the last 2 hours before test (have some breakfast with a drink)

How will we contact you about visits?
We will ask you your preferred method of communication such as e-mail to remind you about your visits.

Will I be paid for my participation?
You will not be paid for taking part in this study.

Why might you be not able to take part in the study?
If you have a history of heart disease (including irregular heartbeats), high blood pressure, problems with the nervous system or taking medicine that alters the cardiovascular system or the nervous system you will not be able to participate. In addition, if you any lower limb muscle or joint problems you will not be able to participate in the study.

What if there is a problem?
Any complaint about the way you have been dealt with during the study or any possible harm you might suffer will be addressed. The detailed information on this is given in Part 2 of this sheet.

Will my taking part in the study be kept confidential?
We will follow ethical and legal practice and all information about you will be handled in confidence. The details are included in Part 2.

This completes Part 1. If the information in Part 1 has interested you and you may want to join the study, please read the additional information in Part 2 before making any decision.

PART 2 OF THE INFORMATION SHEET

What if relevant new information becomes available?
If additional information becomes available during the course of the research, it will mainly be conveyed in the form of e-mail. E-mail or text messages will be used for reminders for you depending on your preference.

What will happen if I don't want to carry on with the study?
If you decide to take part, you can still leave the study at any time without giving a reason. Identifiable data already collected with consent would be retained and used in the study. No further data would be collected or any other research procedures carried out on or in relation to you.

Who is organising and funding the research?
The University of Essex is organising this study. The research team are employees of the University of Essex.

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What if there is a problem or you are unhappy with the conduct of this study?
If you have any concerns or issues with the study please speak to Chris McManus in the first instance, unless you feel it more appropriate to speak to Sarah Mumford, School Manager for the School of Sport, Rehabilitation and Exercise Science (tel 01206 87-3348; e-mail smumfo@essex.ac.uk), or to Sarah Manning-Press, Research Governance and Planning Manager, Research and Enterprise Office (tel 01206 87-3561; e-mail sarahm@essex.ac.uk). In the event that something does go wrong and you are harmed during the research and this is due to someone being at fault, you may have grounds for a legal action for compensation but you may have to pay your legal costs.

All research is looked at by independent group of people, called a Research Ethics Committee, to protect your interests.

If you do decide to take part, you will be given a copy of this information sheet to keep, and will be asked to sign a consent form.

Will my taking part in this study be kept confidential?
If you decide to take part in this study, any information collected about you as part of this project will remain confidential and your identity will not be revealed outside the research and medical team. Any information about you which is collected will have your name and address removed so that you cannot be recognised. Information may be looked at by regulatory authorities to check that the study is being carried out correctly. However, your name and address will not be disclosed as your identity will be allocated a code and in this way will remain anonymous. Data will be handled, processed and stored in accordance with the Data Protection Act 1998 http://www.opsi.gov.uk/acts/acts1998/ukpga_19980029_en_1

What will happen to the results of this study?
Any information collected about you will only be used for the purposes of this project and will be disposed of securely when research is complete. The results may be published in scientific journals, undergraduate reports and used in presentations to healthcare and other interested parties. You will not be personally identified in any report or publication. In line with University guidelines, the anonymised data collected will be stored for a minimum of 6 years. You can request a copy of the findings. You will also be given individual feedback after completion of the study. This is NOT a clinical diagnosis.

For further information about this project please contact
Chris McManus at the University of Essex (Telephone: 01206 874475, e-mail cmcman@essex.ac.uk)

Thank you for taking time to read this Participant Information Sheet.

Appendix 3: Preliminary survey and compression belief questionnaire

Name:

Age:

Average days run per week over the last 6 months:

Average miles per week over the last 6 months:

Best race times in the past year (fill out one or more of the following):

10,000 m:

Half marathon:

Marathon:

Most recent race times in the past year (fill out one or more of the following)

10,000 m:

Half marathon:

Marathon:

Please circle Yes (Y) or No (N)

Are you familiar with (have you heard about) sports compression tights/sleeves or socks?	**Y**	**N**
Have you seen runners wear sports compression tights/sleeves or socks?	**Y**	**N**
Do you personally know anyone who has worn sports compression tights/sleeves or socks?	**Y**	**N**
Have you ever worn sports compression tights/sleeves or socks?	**Y**	**N**

Do you believe sports compression tights/sleeves or socks aid in any of the following;

Training	**Y**	**N**
Competition	**Y**	**N**
Recovery	**Y**	**N**

Appendix 4: Published work

Journal of Biomedical Optics

BiomedicalOptics.SPIEDigitalLibrary.org

Performance comparison of the MOXY and PortaMon near-infrared spectroscopy muscle oximeters at rest and during exercise

Chris J. McManus
Jay Collison
Chris E. Cooper

SPIE.

Chris J. McManus, Jay Collison, Chris E. Cooper, "Performance comparison of the MOXY and PortaMon near-infrared spectroscopy muscle oximeters at rest and during exercise," *J. Biomed. Opt.* **23**(1), 015007 (2018), doi: 10.1117/1.JBO.23.1.015007.

Journal of Biomedical Optics 23(1), 015007 (January 2018)

Performance comparison of the MOXY and PortaMon near-infrared spectroscopy muscle oximeters at rest and during exercise

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Abstract. The purpose of the study was to compare muscle oxygenation as measured by two portable, wireless near-infrared spectroscopy (NIRS) devices under resting and dynamic conditions. A recently developed low-cost NIRS device (MOXY) was compared against an established PortaMon system that makes use of the spatially resolved spectroscopy algorithm. The influence of increasing external pressure on tissue oxygen saturation index (TSI) indicated that both devices are stable between 2 and 20 mmHg. However, above this pressure, MOXY reports declining TSI values. Analysis of adipose tissue thickness (ATT) and TSI shows a significant, nonlinear difference between devices at rest. The devices report similar TSI (%) values at a low ATT (<7 mm) (PortaMon minus MOXY difference is $+1.1 \pm 2.8\%$) with the major subsequent change between the devices occurring between 7 and 10 mm; at ATT values >10 mm the difference remains constant ($-14.7 \pm 2.8\%$). The most likely explanation for this difference is the small source–detector separation (2.5 cm) in the MOXY resulting in lower tissue penetration into muscle in subjects with higher ATT. Interday test–retest reliability of resting TSI was evaluated on five separate occasions, with the PortaMon reporting a lower coefficient of variation (1.8% to 2.5% versus 5.7% to 6.2%). In studies on male subjects with low ATT, decreases in the TSI were strongly correlated during isometric exercise, arterial occlusion, and incremental arm crank exercise. However, the MOXY reports a greater dynamic range, particularly during ischemia induced by isometric contraction or occlusion ($\Delta 74.3\%$ versus $\Delta 43.7\%$; hyperemia MAX—occlusion MIN). This study shows that in this subject group both MOXY and PortaMon produce physiologically credible TSI measures during rest and exercise. However, the absolute values obtained during exercise are generally not comparable between devices unless corrected by physiological calibration following an arterial occlusion. [DOI: 10.1117/1.JBO.23.1.015007]

Keywords: near-infrared spectroscopy; reliability; muscle oxygen saturation; isometric exercise.

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1 Introduction

The use of wearable devices or wearable biosensors, which allow the continuous monitoring of physiological signals, is important for better monitoring of active lifestyles and the diagnosis and treatment of diseases.[1] Near-infrared spectroscopy (NIRS) is a noninvasive technique capable of providing valuable functional insights into skeletal muscle oxidative metabolism *in vivo* during exercise, in healthy and clinical populations.[1] NIRS directly measures the oxygen-dependant absorption of hemoglobin (Hb) in the microcirculation blood vessels (i.e., arterioles, capillaries, and venules) and myoglobin (Mb) in the muscle cytoplasm.[2]

Dependent on the NIRS device and illumination type, it is possible to retrieve absolute and/or relative concentration values of oxyhemoglobin (O_2Hb) and deoxyhemoglobin (HHb), and a derived parameter, total-hemoglobin ($tHb = O_2Hb + HHb$).[3] These values are in a large part representative of tissue capillaries, arterioles, and venules because, in larger blood vessels, NIR light is fully absorbed by the high hemoglobin concentration.[4] A further measurement, tissue saturation index (TSI) represents the ratio of oxygenated ($O_2Hb + O_2Mb$) concentration to total (tHb + tMb) concentration, reporting on the dynamic balance between O_2 supply and O_2 consumption. Taken as a whole, the range of muscle NIRS parameters can provide information regarding changes in key dynamic physiological indicators, such as blood flow, oxygen extraction, and oxygen consumption; muscle NIRS studies are therefore relevant in the evaluation of exercise performance, exercise tolerance,[1] and exercise training adaptation that can influence the balance between muscle O_2 delivery and muscle utilization.[5]

The use of NIRS as a research tool is well established for studying exercise physiology changes in groups of subjects.[1,6] Sports science applications could include monitoring changes in muscle blood flow and oxidative capacity as a function of training.[4] In support of this, positive peripheral muscle oxygenation adaptations have been reported as a consequence of cycling sprint interval training, demonstrating that NIRS has the potential to assess the effectiveness of training interventions at the level of the individual athlete.[7] To be effective outside the research laboratory, in an applied exercise environment, there is a requirement for low-cost, portable NIR technology with telemetric capability with the ability to withstand the rigors of sporting environments such as in swimming,[8] short track speed skating,[9] and trail running.[10]

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Past studies comparing NIRS monitors have highlighted discrepancies in the values obtained at rest and during exercise in human[11–14] and animal[15] systems. The differences between monitors are likely to be in part associated with the measurement site and spacing of the probes.[16,17] The specific optical properties of the system, whether laser, white light or light-emitting diode (LED)-based, as well as the specific NIR wavelengths monitored, could also contribute to differences between systems. These physical properties are most likely reflected in time resolution, signal:noise, and reproducibility. However, the absolute numbers of the derived parameters are highly dependent on the algorithms used in the calculations. In terms of measurements of TSI, these methods attempt to remove or correct for the contributions of light scattering and then fit the remaining optical density changes to the known NIR spectra of the hemo(myo)globin chromophores. Assumptions are also made about light transport generally assuming the diffusion model.

Time of flight or frequency domain measurements can be used to measure absolute chromophore concentrations, but such devices are currently unlikely to be cheap enough, or portable enough, to be of use for routine physical activity measurements. Manufacturers have therefore focussed on developing methods that only require continuous wave light detection, relying on the use of multiwavelength or multidistance analysis to correct for the scattering. Multiwavelength measures, e.g., using second derivative spectroscopy,[18,19] are now rarely used. However, the use of multidistance methods has significantly expanded in recent years. In a recent review, only 1 of 13 current devices measured optical density at a single source:detector distance.[1]

In general, multidistance NIR systems correct for light scattering by one of two methods. The most common method used in historical terms is spatially resolved spectroscopy (SRS) This measures the slope of the optical density change as a function of multiple distances. Theoretically, the difference in these distances should be small compared to the average source:detector separation. This enables the calculation of scaled absorption coefficient (μ_a) measures, which can allow absolute values of chromophore ratios, such as tissue oxygen saturation.[20] The major commercial incarnations of the SRS system historically are the Hamamatsu NIRO and the Artinis OxyMon systems. Alternative spatial resolution (SR) methods use a larger separation among measurement sites; light transport models assuming the shorter distance predominantly measures surface tissues and the longer distance deeper tissues are used to calculate a tissue oxygen saturation for the deeper (muscle/brain) region of interest.[21] The predominant commercial incarnation of this SR method historically is the Medtronic INVOS™ and more recently the FORE-SIGHT ELITE® and the Nonin EQUANOX™ systems.

Although one can assume that two different devices both using the SRS measurements will generally report similar muscle oxygen saturations, the same cannot be assumed between devices using SR methods, given the variety of algorithms in use,[22] nor of course between an SRS device and an SR device.[23] SRS systems have been widely used in exercise physiology and sports science.[1,3] Recently, a new low-cost SR-based device, the MOXY monitor, has been marketed to athletes as a training tool to inform the user of exercise intensity.[10,24] The PortaMon, a widely used, portable, SRS oximeter has previously demonstrated a high level of reliability at rest[25] and during isotonic, multijoint resistance exercise.[26] Conversely, no studies investigating the test–retest reliability of the MOXY device have been conducted.

It would be helpful if users of NIRS devices could be confident that the extensive historical SRS literature on exercise physiology and sports science can be used to help inform their use of this new SR device. The purpose of the study was therefore to compare these two portable, wireless NIRS devices under a variety of resting and dynamic conditions. These conditions include (1) the influence of varying external pressure at rest, (2) test–retest reliability and sensitivity at rest, (3) during isometric leg extension exercise, (4) during dynamic arm-crank exercise, and (5) during an arterial occlusion.

2 Methods

2.1 *NIRS Devices*

The two NIRS devices used in the assessment of muscle oxygen saturation include the PortaMon (PortaMon, Artinis, Medical System) and MOXY muscle monitor (Fortiori Design LLC).

The PortaMon is a compact ($83 \times 52 \times 20$ mm) and lightweight (84 g) NIRS system. It is a dual-wavelength (760 and 850 nm), continuous wave system, containing three pairs of LEDs in an SRS configuration with a source–detector spacing of 30, 35, and 40 mm. The device simultaneously uses the modified Beer–Lambert law and SRS methods to calculate the absolute concentration of tissue oxy(+myo)hemoglobin, (O_2Hb), deoxyhemo(+myo)globin (HHb), and total hemo(+myo)globin (tHb). As such, tissue oxygen saturation (TSI) is expressed in % and calculated as $[O_2Hb]/([O_2Hb] + [HHb]) \times 100$, which is the ratio of HbO_2 to tHb. TSI reflects the dynamic balance between O_2 supply and consumption. During all testing, the system was connected to a personal computer via Bluetooth™ technology for data acquisition (10 Hz), analog-to-digital conversion and subsequent analysis.

The MOXY is a self-contained, compact ($61 \times 44 \times 21$ mm), and lightweight (48 g) NIRS system. It employs four wavelengths of NIR light at 680, 720, 760, and 800 nm (Schmitz, 2015) and the sensor contains a single LED and two detectors in placed 12.5 and 25.0 mm from the source. The MOXY device reports a change in total tissue hemo(+myo)globin (tHb) and tissue oxygenation (TSI). During all testing, the system was connected to a personal computer via a commercially available software program (Peripedal ©) to provide a graphic display of the data. Data acquisition (2 Hz) was obtained from the sensors internal memory.

2.2 *Testing the Influence of External Pressure*

In order to minimize movement artifacts when fixing NIRS devices to the tissue, a variety of supportive bandages or neoprene sleeves are generally used. These sleeves apply external pressure to the device and the surrounding limb area under compression. The influence of external pressure on NIRS derived values is largely undiscussed in the literature, yet if found that TSI data differ due to varying low external pressure this is of importance for both the research and applied user community.

A repeated-measures experimental design was used to determine the influence of external pressure on the reliability of two portable NIRS devices. Four recreationally active male participants ([mean ± SD] age 22.75 ± 5.56 years, body mass 78.03 ± 4.38 kg, height 1.86 ± 0.1 m, vastus lateralis (VL) skinfold thickness 8.30 ± 2.51 mm) volunteered to participate in this study. None of the participants had known health problems or any lower extremity muscle or joint injury. Participants

were asked not to perform any strenuous exercise or consume caffeine for at least 24 h prior to visiting the laboratory.

Participants were required to visit on one occasion. All testing was performed in a controlled laboratory environment (~20°C) at the University of Essex Clinical Physiology Laboratory. Upon arrival, following the collection of descriptive measures, participants performed 10 min of supine rest on a medical examination bench. The first portable NIRS device was then positioned on the belly of the vastus lateralis, midway between the greater trochanter and the lateral epicondyle of the femur. NIRS devices were placed precisely on the VL, whereby the middistance between the closest emitting diode and detector for each device was aligned with the VL location. To ensure the optodes and detector did not move relative to the participants' skin, the device was fixed into position using a waterproof adhesive tape. In addition, bodily hair at or around the sensor placement area was removed from the skin and participants were asked not to moisturize the area on the day of testing. A portable pressure monitor (PicoPress, MircoLabs, Italy) was used to assess the external pressure applied to the leg. An air-filled bladder was placed on the medial aspect of the thigh, at the same vertical alignment to the NIRS device location. A surgical marker pen was used to mark the position of NIRS device and bladder placement in order to identify any movement during testing and ensure the second NIRS device was placed at the same location.[7] A black neoprene thigh sleeve (Mueller, Wisconsin) was wrapped around the leg to secure the NIRS device in place firmly against the skin and also ensure that no external light would be received by the device detectors.

Incremental external pressure (mmHg) was applied to the surrounding area, encompassing the NIRS device and pressure monitor bladder, using an aneroid sphygmomanometer (Welch Allyn Inc., New York, New York) connected to a thigh blood pressure cuff (Accoson Works, Essex, United Kingdom). All measurements were recorded in a supine position; with the order of NIRS device application counterbalanced. Initial external pressure applied was 2 mmHg as a result of the neoprene strapping, prior to inflating a blood pressure cuff in a stepwise manner.

Initially, the investigator visually observed the live NIRS data on a personal computer until a stable value was achieved and collected 60 s of data. Stability was defined as a TSI variation <2% over 30 s.[27] This procedure was repeated for all NIRS devices. After 4 min of baseline data collection with the neoprene strap applying 2 mmHg, the sphygmomanometer was inflated to elicit a pressure of 5 mmHg, with 5 mmHg increments every 4 min thereafter, up to and including 30 mmHg. The data acquired from the PortaMon system were downsampled from 10 to 2 Hz to allow for comparison with the MOXY system. Values are reported as average absolute TSI, calculated from the final 60 s of each 4 min period. Descriptive statistics are presented as mean (TSI) unless otherwise stated. A simple linear regression was then used to calculate slopes of the NIRS device versus external pressure. Subsequently, the TSI of PortaMon minus MOXY at incremental external pressures could be fitted by a sigmoid curve. All analyses were performed using Graphpad Prism 7 (Graphpad Software, San Diego, California).

2.3 *Comparing Devices at Rest*

Muscle oxygenation of the dominant vastus lateralis muscle of each participant was measured with two MOXY (MOXY^1 and MOXY^2) and two PortaMon (PortaMon^1 and PortaMon^2) devices to assess between and within-device variation. Twenty-one male ([mean ± SD] age 22.33 ± 4.84 years, body mass 78.24 ± 10.62 kg, height 1.79 ± 0.1 m, VL skinfold thickness 11.59 ± 5.09 mm) and nine female participants (age 21.67 ± 2.40 years, body mass 65.14 ± 7.44 kg, height 1.69 ± 0.04 m, VL skinfold thickness 26.36 ± 4.77 mm) volunteered to participate in this study. The experimental protocol involved a single visit to the laboratory. Upon arrival, participants performed 10 min of supine rest on a medical examination bench. The first of four NIRS devices was positioned on the vastus lateralis muscle (as described in Sec 2.2), and all measurements were recorded in a supine position. Using a portable pressure monitor, care was taken to ensure the same external pressure (~8 mmHg) was exerted by the neoprene strapping surrounding the NIRS device, during each condition. Device order was counterbalanced using a Latin square design. The investigator visually observed the live NIRS data on a personal computer until a stable value was achieved (minimum 2 min) and collected 60 s of data. This procedure was repeated for all four NIRS devices.

Descriptive statistics are presented as mean ± SD unless otherwise stated. A one-way analysis of variance (ANOVA) was used to compare mean values of resting TSI between the four NIRS devices. A Tukey's range test was used for *post hoc* multiple comparisons. Subsequently, an unpaired *t*-test was performed to compare the combined average of two similar devices at rest (Mean TSI (PortaMon + PortaMon) versus mean TSI (MOXY + MOXY). Accuracy was calculated as the mean absolute difference, using Bland–Altman agreement plots (±2SD) between resting TSI. A 95% confidence interval of the mean (95%CL) is also presented for each case. The difference between devices was calculated as the mean TSI of PortaMon minus MOXY. A Pearson's product-moment correlation analysis was used to compare the association between resting values of TSI and quadriceps skinfold thickness [adipose tissue thickness (ATT) = 0.5 × mean skinfold thickness]. Significance was set at $P < 0.05$. All statistical analyses were performed using Graphpad Prism 7 (Graphpad Software, San Diego, California).

2.4 *Test–Retest Reliability and Sensitivity of Devices at Rest*

Five male participants ([mean ± SD] age 21.2 ± 2.7 years, body mass 71.5 ± 7.7 kg, height 1.78 ± 0.1 m, and VL skinfold thickness 11.3 ± 5.3 mm) undertook repeated resting measures assessing vastus lateralis TSI (%) for a total of five occasions. Each visit to the laboratory was separated by at least 24 h, thereby providing a method of assessing interday test–retest reliability of four NIRS devices (MOXY^1, MOXY^2, PortaMon^1, and PortaMon^2). Upon arrival on each occasion, participant's vastus lateralis was identified as described in Sec 2.2. Neoprene strapping was carefully tightened around the NIRS device to ensure a pressure of 8 mmHg was exerted. The same researcher attached each device on every occasion to minimize intertester variability. After 10 min supine rest, the investigator visually observed the live NIRS data on a personal computer until a stable value was achieved (minimum 2 min) and collected 60 s of data. This procedure was repeated for all four NIRS devices using a Latin square design.

Descriptive statistics are presented as mean ± SD unless otherwise stated. The mean participant TSI for each NIRS device was used as an indicator of test–retest reliability.[28] The coefficient of variation (CV) was calculated as a characteristic of the

performance of within-subject evaluation,[29] with a CV below 5% to 10% considered as acceptable absolute reliability.[26]

All statistical analyses were performed using Microsoft Excel and GraphPad Prism 7.

2.5 *Comparing Devices During Isometric Exercise*

A repeated isometric quadriceps contraction exercise protocol was implemented to compare the delta (Δ) TSI between four NIRS devices (MOXY[1], MOXY[2], PortaMon[1], and PortaMon[2]). The same five male participants ([mean ± SD] age 21.2 ± 2.7 years, body mass 71.5 ± 7.7 kg, height 1.78 ± 0.1 m, and VL skinfold thickness 11.3 ± 5.3 mm) who underwent the test–retest reliability assessment at rest (see Sec. 2.4), participated in a quadriceps isometric contraction task. Participants were asked not to perform any strenuous exercise or consume caffeine for at least 24 h prior to visiting the laboratory.

During the initial visit, the participant's maximal voluntary isometric contraction (MVC) was determined. Prior to the isometric contraction task, a nonspecific warm-up on a cycle ergometer (Monark, 824E) was completed, before performing an MVC of the knee extensors using an isokinetic dynamometer (KinCom, Chattanooga Inc., Tennessee). Participants were positioned upright on the dynamometer ensuring the knee joint (lateral femoral epicondyle) and dynamometer axes were accurately aligned and stabilized using leg, waist, and chest straps to minimize trunk movement during testing. The seat height and distance from the axis were recorded to ensure accurate repeat positioning. The dominant leg was then fixed at a 60 deg angle and three submaximal repetitions of a 5-s continuous quadriceps isometric contraction were performed. Participants then performed three maximal contractions interspersed with a 60-s rest period. The best of the three contractions was considered the maximal isometric force and values for 30% and 50% MVC were then calculated.

During the second visit, after resting data were collected from all four NIRS devices (see Sec. 2.3), the final NIRS device was left attached to the participant's leg for the duration of the quadriceps isometric contraction task. Participants were positioned on the dynamometer (as described above) with no warm-up. After a stable pretest TSI value was attained, the participants were instructed to perform two 30-s sustained isometric quadriceps contractions to the previously defined values of their MVC (30% and 50%) interspersed by a 3-min rest period. TSI was continuously monitored throughout the procedure. This procedure was repeated for visits 3, 4, and 5 using a different NIRS device during the isometric contraction task.

Due to potential differences in resting values for the two devices (2.3; 2.4), TSI was reported as a change from pretest (60 s averaging before each test). Maximum and minimum TSI values were calculated as a three-second average surrounding the highest and lowest values during each of the two isometric contractions. The Δ in TSI was therefore calculated as the maximum value minus the minimum value during each 30 s contraction, e.g., TSI Max − TSI Min = ΔTSI.[8]

Descriptive statistics are presented as mean ± SD unless otherwise stated. A one-way analysis of variance (ANOVA) was used to compare mean values of Δ TSI between the four NIRS devices. A Tukey's range test was used for *post hoc* multiple comparisons. ICC was calculated to compare between-device reliability at 30% and 50% MVC (Δ TSI). Accuracy was calculated as the mean absolute difference, using Bland–Altman agreement plots (±2SD) between resting TSI. A 95% confidence interval of the mean (95%CI) is also presented for each case. The difference between devices was calculated as the mean TSI of MOXY minus PortaMon. All statistical analyses were performed using Graphpad Prism 7 (Graphpad Software, San Diego, California). The studies undertaken all received ethical approval from the University of Essex ethical committee and participants provided written informed consent before inclusion.

2.6 *Comparing Devices During Dynamic Exercise and Occlusion*

An incremental asynchronous arm-crank exercise protocol, followed by a 5-min arterial occlusion, was undertaken to compare TSI values between two NIRS devices (MOXY[1] versus PortaMon[1]). Based on the effect size observed between NIRS devices during isometric exercise at 50% MVC, a power analysis for a dependant sample *t*-test was conducted using G*Power to determine a sufficient sample size using an alpha of 0.05, a power of 0.80, a large effect size ($dz = 2.9$), and two tails.[30] Based on the aforementioned assumptions, the desired sample size is 4. We elected to recruit an additional two participants to allow for participants terminating the arterial occlusion early due to the sensation of pain. Six male participants ([mean ± SD] age 23.7 ± 4.1 years, body mass 73.3 ± 5.2 kg, ATT 2.7 ± 1.0 mm) undertook the exercise and occlusion task, requiring two separate visits to the laboratory, separated by 3 to 7 days. On arrival, following basic anthropometrical measures, the participant confirmed their dominant arm (all participants' self-reported right hand dominance) and ATT was assessed at the muscle belly of the biceps brachii, 8 cm above the midarm fold. The first NIRS device was positioned on the biceps brachii, where the 8 cm marker was used to determine the midpoint between the device emitter and detectors. The biceps brachii were chosen as previous literature has reported this muscle eliciting the greatest decrease in tissue oxygenation index during arm cranking compared with the triceps brachii, brachioradialis, and anterior deltoid.[5] A portable pressure monitor was used to ensure a similar external pressure was exerted by the black crepe bandage used to hold the device in place. Subsequently, the participant's sat upright, with hands in a rested position until a stable TSI value was achieved (minimum 2 min) and a resting baseline was obtained over a 5-min period.

Prior to arm cranking, participants were positioned with the crank axis aligned to shoulder height, at a distance that allowed a slight bend in the elbow when arms were extended. A chest strap was applied to minimize trunk movement during testing and seat/crank height were recorded to ensure accurate repeat testing. Participants were required to arm-crank at 60 rpm beginning at 0 Watts (W) and increasing by 25 W every 2 min. The exercise end-point was determined when cadence fell below 60 rpm for 3 consecutive seconds.

Following completion of the incremental arm-crank exercise task, participants remained seated with hands in a rested position for 5 min prior to an arterial occlusion. To enable a physiological calibration of raw TSI values by identifying the participant's notional minimum and maximum TSI, an arterial occlusion was applied for 5 min using an automated pneumatic cuff inflator (Hokanson, Bellevue) positioned at the proximal aspect of the humerus, applying 295 to 305 mmHg of pressure. After a 5-min occlusion, the cuff was released and participant's continued to rest for a further 5 min period. This procedure was repeated for the second visit using the alternative NIRS device. Although we cannot be sure that this value exactly corresponds

to complete deoxygenation of hemoglobin and myoglobin, in all subjects this time was sufficient to result in a stable minimum in saturation value significantly lower than any observed during exercise.

Initially, the data acquired from the PortaMon system were downsampled from 10 to 2 Hz to match that of the MOXY system. Following this, both device data-sets were smoothed by calculating the 3 s moving average at 2 Hz. To normalize the NIRS signal and achieve a physiological calibration, the average value of the final 30 s was used to determine notional 0% oxygenation (calibration) and the 30 s peak hyperemic response upon release of the cuff was used to indicate notional 100% oxygenation (we use the term "notional" as we cannot be absolutely sure that the lower value could not be decreased further by adding an ischemic exercise component, not that the upper value could not be increased by hyperoxia and/or methods to increase blood flow or decrease oxygen consumption; however, the current physiological calibration has the advantage of being relatively easy to implement and in common use in the field). The Δ in TSI during the occlusion task was calculated as the maximum value minus the minimum value, identified from the onset of the cuff inflating to the period following the hyperemic response upon cuff release.

During the incremental test, TSI was established for each power output as the final 30 s average for each stage. These values were subtracted from the resting baseline TSI to provide a delta (Δ) raw TSI and subsequently converted to a calibrated (% calibration) value.

Descriptive statistics are presented as mean [95% CI] unless otherwise stated. Paired *t*-tests were used to compare performance outcomes of the arm-crank test and compare device minimum, maximum, and delta values for raw (TSI) and calibrated (% calibration) data during the occlusion. Furthermore, a repeated measure ANOVA was conducted to compare values obtained during the incremental arm-crank test for each power output. Significant *F* ratios were examined on a *post hoc* basis using an uncorrected Fisher's LSD test. Where data were not obtained for all participants at peak power output (i.e., only three participants completed the 100-W stage), a paired *t*-test was conducted on the smaller sample size to compare differences between devices. The incremental data are reported as the change from resting baseline in both raw (Δ TSI) and calibrated units (Δ calibration %). A simple linear regression was then used to calculate slopes of the NIRS device versus power output.

3 Results

3.1 *Testing the Influence of External Pressure*

There was a significant correlation between TSI and external pressure for both MOXY and PortaMon devices [Fig. 1(a)], in both cases showing a drop in TSI with increasing pressure. The slope was significantly steeper for the MOXY than the PortaMon (a slope of $-0.38 \pm 0.09\%$ TSI per mmHg for the MOXY compared to -0.08 ± 0.03 for the PortaMon). The PortaMon reports a lower resting TSI (%) at low pressure (<20 mmHg); with the major subsequent change between the devices occurring between 20 and 30 mmHg [Fig. 1(b)]. Therefore, to decrease variability, the subsequent studies were all undertaken at lower than <20 mmHg, with a target external pressure of 8 mmHg when participants were supine.

3.2 *Comparing Devices at Rest*

Resting TSI of male and female participants for four NIRS devices is provided in Table 1. A one-way ANOVA of mean resting TSI among the four NIRS devices for female participants demonstrated a significant difference ($P < 0.05$), with *post hoc* multiple comparisons showing a significant difference between MOXY and PortaMon devices ($MOXY^1$ versus $PortaMon^1$; $MOXY^1$ versus $PortaMon^2$; $MOXY^2$ versus $PortaMon^1$; $MOXY^2$ versus $PortaMon^2$ = $P < 0.05$). Conversely, no difference was found between devices for male participants.

As no significant difference was found at rest between either $MOXY^1$ versus $MOXY^2$ or $PortaMon^1$ versus $PortaMon^2$, the combined mean TSI for MOXY ($MOXY^1$ and $MOXY^2$) and PortaMon ($PortaMon^1$ and $PortaMon^2$) at rest for male and female participants (Table 1) was compared using an unpaired *t*-test. Mean female MOXY TSI ($90.9 \pm 5.1\%$) was significantly higher than the PortaMon ($76.7 \pm 2.6\%$) [$t(16) = 7.4$, $P < 0.05$]; however, no significant difference was observed in male participants between the MOXY ($74.3 \pm 12.8\%$) and PortaMon ($72.2 \pm 3.5\%$) devices.

At rest, Bland–Altman plots of male participants [Fig. 1(c)] suggest the MOXY device reports a higher saturation value at higher resting TSI and a lower value at lower resting TSI. So, the lack of a significant difference of the mean value masks a real measurement difference between the devices even in male subjects. Bland–Altman plots of resting female participants [Fig. 1(d)] illustrate a consistently higher TSI with the MOXY device versus PortaMon, regardless of average TSI, consistent with the difference in the mean values.

Vastus lateralis skinfold thickness (mm) and resting TSI (%) are highly correlated using the combined mean TSI MOXY ($r = 0.70$, $P < 0.01$) and PortaMon device ($r = 0.73$, $P < 0.01$). Linear regression of VL skinfold thickness and TSI [Fig. 2(a)] shows the difference between the slopes (MOXY versus PortaMon) are significantly different [$F(1, 54) = 11.97$, $P = 0.001$]. The MOXY device shows a regression slope ($y = 1.12 * x + 61.22$), steeper than that of the PortaMon ($y = 0.34 * x + 68.16$). This indicates that as skinfold thickness increases, the rise in TSI is greater with the MOXY. The difference between the two values is nonlinear with respect to ATT [Fig. 2(b)]. The PortaMon and MOXY devices report similar TSI (%) values at a low ATT (<7 mm); with the major subsequent change between the devices occurring between 7 and 10 mm; at ATT values >10 mm the difference remains constant. The data fit well to a sigmoidal dose response relationship. At the lowest ATT, the (PortaMon minus MOXY) difference is $+1.1 \pm 2.8\%$; (mean + SEM), at the highest ATT the difference is $-14.7 \pm 2.8\%$; the 50% change occurs at 8.5 ± 0.6 mm ATT.

3.3 *Test–Retest Reliability of Devices at Rest*

The CV for all NIRS devices are listed in Table 2. The mean CV values were lower for the PortaMon (<2.5%) when compared with the MOXY devices (5.7% to 6.2%); however, both devices were below the acceptable threshold of 10%. The SD of the individual devices highlights a smaller measurement variation when using the PortaMon, suggesting that the intersubject variation across repeated measures is less than the MOXY device.

3.4 *Comparing Devices During Isometric Exercise*

Mean torque of 30% and 50% MVC was 256.9 ± 43.5 and 428.2 ± 72.5N, respectively. A one-way ANOVA of ΔTSI

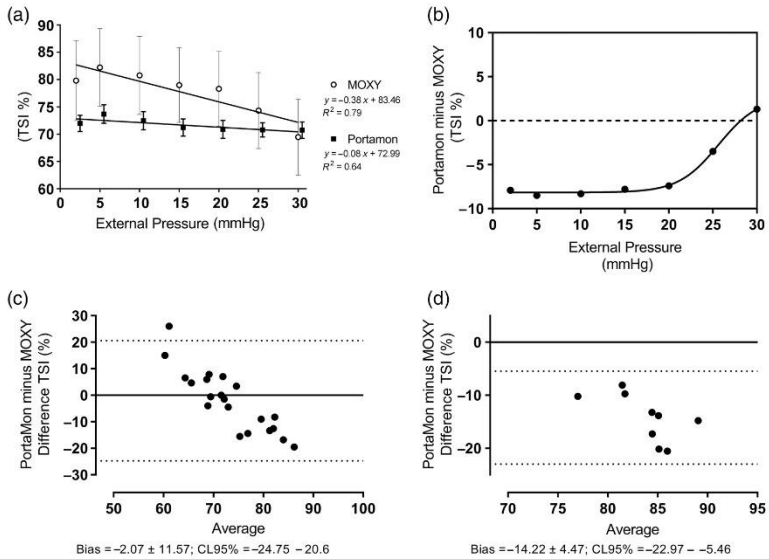

Fig. 1 (a) Linear regression showing TSI as a function of external pressure (mmHg) (mean ± SEM), (b) PortaMon minus MOXY (TSI) as a function of external pressure (mmHg). Data fit using nonlinear regression to a sigmoidal curve for illustrative purposes and (c) Bland–Altman plots of resting TSI of males ($n = 21$) and (d) females ($n = 9$) using the combined average of MOXY and PortaMon devices. Each plot represents the difference versus the average of the two devices. Dotted lines represent the ±2SD limits of agreement.

Table 1 Male and female mean TSI of four NIRS devices at rest.

	Male TSI (%)	Female TSI (%)
	Mean ± SD [95% CI]	Mean ± SD [95% CI]
MOXY[1]	75.2 ± 13.1 [69.3, 81.2]	92.7 ± 5.0* [88.8, 96.6]
MOXY[2]	73.3 ± 12.8 [67.5, 79.2]	89.1 ± 6.3* [84.3, 94.0]
PortaMon[1]	72.8 ± 3.5 [71.2, 74.4]	77.3 ± 2.7 [75.2, 79.4]
PortaMon[2]	71.6 ± 3.7 [70.0, 73.3]	76.1 ± 2.8 [74.0, 78.3]
Combined MOXY	74.3 ± 12.8 [68.5, 80.1]	90.9 ± 5.1** [87.0, 94.9]
Combined PortaMon	72.2 ± 3.5 [70.6, 73.8]	76.7 ± 2.6 [74.7, 78.7]

*Significantly different from PortaMon[1] and PortaMon[2] ($P > 0.05$).
**Significantly different to Combined PortaMon ($P > 0.001$).

during 30% and 50% MVC between the four NIRS devices demonstrated a significant difference ($P < 0.05$), with *post hoc* multiple comparisons showing a significant difference between MOXY and PortaMon devices (MOXY[1] versus PortaMon[1]; MOXY[1] versus PortaMon[2]; MOXY[2] versus PortaMon[1]; MOXY[2] versus PortaMon[2] = $P < 0.05$). Table 3 displays the ΔTSI values.

No significant difference was found during the isometric quadriceps exercise between either MOXY[1] and MOXY[2] or PortaMon[1] and PortaMon[2]. As such, the combined group averaged data ($n = 5$) for MOXY (MOXY[1] and MOXY[2]) and PortaMon (PortaMon[1] and PortaMon[2]) during the quadriceps isometric contraction task is shown as a composite graph in Fig. 3(a). The general trend was similar for all five participants among devices. For both systems, an immediate decrease in TSI at the onset of isometric contraction (30% MVC) was observed. This recovered rapidly following contraction cessation and, in some cases, overshooting (a hyperaemic response). A larger decrease in TSI was observed at 50% MVC and returning to resting at task cessation. Bland–Altman plots indicate that the MOXY reports consistently higher ΔTSI at both 30% [Fig. 3(b)] and 50% [Fig. 3(c)] MVC, with a trend showing the greater the average ΔTSI, the greater the difference.

3.5 *Comparing Devices During Dynamic Exercise and Occlusion*

Peak performance measures, ATT, external pressure applied by the NIRS devices, TSI data during the incremental arm-crank test, and subsequent arterial occlusion are presented in Table 4. No significant differences were observed for peak power output or time to exhaustion between trials and external pressure was applied between 9 and 13 mmHg. During the arterial occlusion and the following reactive hyperaemia, significant differences were observed between NIRS devices for minimum, maximum,

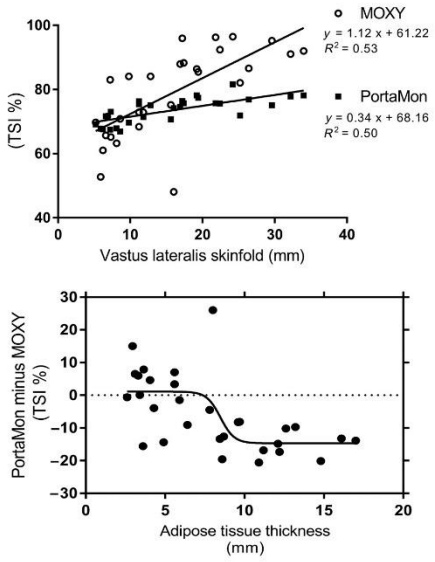

Fig. 2 (a) Relationship between mean TSI and vastus lateralis skinfold (mm) using the combined average of MOXY and PortaMon devices and (b) PortaMon minus MOXY (TSI) as a function of ATT (mm). Data fit using nonlinear regression to a sigmoid dose response curve.

and delta TSI. The MOXY device repeatedly reported a greater delta TSI when compared with the PortaMon ($p < 0.01$).

During the incremental arm-crank test, between-device TSI differences were observed at 25 W when comparing raw TSI values. In the postexercise hyperaemic period, the MOXY device also reported a significantly greater maximum value compared with the PortaMon ($p < 0.01$). However, these differences were not observed when the TSI range of the devices was calibrated to the min and max TSI associated with the arterial occlusion.

Despite the lack of significant differences seen at individual power values using the calibrated values, when the data are taken as a whole a subtle distinction can be observed. Figure 4 demonstrates the relationship between increasing power output and a progressive decrement in TSI. The regression slope was not significantly different ($P = 0.18$) between the MOXY and the PortaMon device for the raw TSI values [Fig. 4(a)] (a slope of $-0.16 \pm 0.02\%$ TSI per 1 W for the MOXY compared to -0.12 ± 0.005 for the PortaMon); however, the lines are not identical due to a significant difference in the intercepts [$F(1,7) = 47.06$, $P =< 0.01$]. A similar result is present when comparing the regression slopes of the calibrated values [Fig. 4(b)] between devices ($P = 0.45$), reporting similar decrements in TSI (% calibrated) per 1 W increase (MOXY $= -0.23 \pm 0.03\%$; PortaMon $= -0.26 \pm 0.006\%$), yet a statistically significant difference in the intercepts [$F(1,7) = 12.95$, $P =< 0.01$]. The difference in the intercepts appears to be due to a lower value of the MOXY after warm-up compared to baseline (the 0-W point is arm cranking with zero resistance compared to complete rest).

Table 2 Test–retest measures of device reliability (TSI) at rest.

	MOXY[1]		MOXY[2]		PortaMon[1]		PortaMon[2]	
	Mean ± SD	CV (%)	Mean ± SD	CV (%)	Mean ± SD	CV (%)	Mean ± SD	CV (%)
Subject 1	52.9 ± 4.4	8.4	52.7 ± 3.5	6.7	67.9 ± 1.0	1.5	66.6 ± 1.2	1.7
Subject 2	87.8 ± 4.8	5.4	82.9 ± 4.9	5.9	74.7 ± 1.9	2.5	73.8 ± 1.3	1.8
Subject 3	56.9 ± 5.5	9.6	53.7 ± 4.9	9.2	66.0 ± 1.1	1.7	64.7 ± 2.6	4.1
Subject 4	87.2 ± 3.1	3.6	84.9 ± 3.3	3.9	71.3 ± 0.8	1.1	70.0 ± 1.6	2.3
Subject 5	71.8 ± 2.7	3.8	70.1 ± 1.9	2.7	72.7 ± 1.6	2.2	71.1 ± 1.8	2.6
Grouped data								
CV (%)	6.2 [2.8, 9.5]		5.7 [2.5, 8.8]		1.8 [1.1, 2.5]		2.5 [1.3, 3.7]	

Note: CV, coefficient of variation [95% confidence interval].

Table 3 Δ change in TSI (%) values during 30 s quadriceps isometric contraction task at 30% and 50% maximal voluntary contraction (MVC) of each NIRS device Mean ± SD (range).

	MOXY[1]	MOXY[2]	PortaMon[1]	PortaMon[2]
ΔTSI 30% MVC (%)	36.5 ± 7.3[a] (28.4–47.7)	37.9 ± 14.4[a] (15.2–55.2)	9.4 ± 4.4 (5.0 – 16.3)	8.3 ± 4.8 (2.9–15.7)
ΔTSI 50% MVC (%)	57.3 ± 14.9[b] (41.3–77.2)	60.8 ± 13.7[b] (42.3–75.9)	14.2 ± 2.3 (11.7–16.7)	14.8 ± 4.3 (9.9–19.7)

[a]Significant difference from PortaMon[1] and PortaMon[2] at 30% MVC ($P > 0.05$).
[b]Significant difference from PortaMon[1] and PortaMon[2] at 50% MVC ($P > 0.05$).

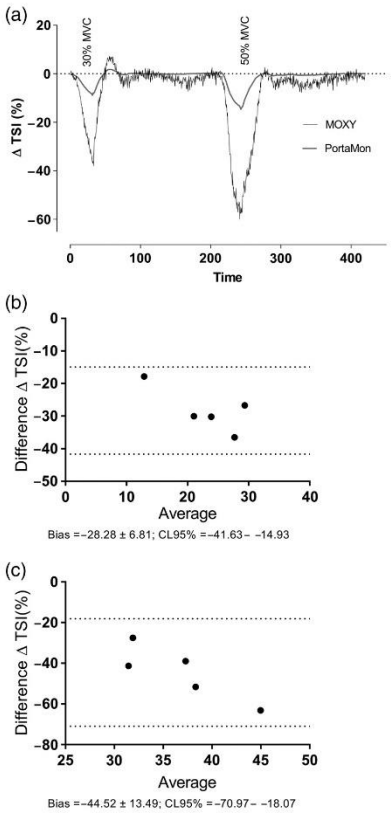

Fig. 3 (a) Group changes in tissue saturation index (ΔTSI) during 30% and 50% isometric MVC tasks and (b) Bland–Altman plots of ΔTSI at 30% MVC ($n = 5$) and (c) 50% MVC ($n = 5$) using the combined average of MOXY and PortaMon devices. Each plot represents the difference versus mean Δ value measured as the average of the two MOXY devices compared to the two PortaMon devices. Dotted lines represent the ±2SD limits of agreement.

Figure 5 shows the raw and calibrated TSI traces during incremental arm cranking and the subsequent arterial occlusion for individual participants. It is evident from these figures that both devices follow a similar trend within individuals between both MOXY and PortaMon devices. Interestingly, following a rapid desaturation during the initial two stages of the arm-crank test (0 and 25 W), the TSI trace for participant 3 increased from 50 W to the end of the test. This physiological observation was reproduced by both devices for this individual on separate testing occasions.

4 Discussion

This current study compared two portable, wireless NIRS devices. While the measurement of muscle oxygen saturation correlated between the MOXY and PortaMon under a variety of resting and dynamic conditions, significant differences were noted, both with respect to device reliability and absolute values of saturation.

4.1 *Comparing Devices at Rest*

Light entering the surface above the vastus lateralis will pass through skin and adipose tissue layers before entering the muscle. It is generally assumed that NIR light reaching a detector has an effective penetration depth of ~50% to 60% of the interoptode distance.[31] Therefore, the PortaMon (maximum source:detector separation of 40 mm) would be expected to detect more light from the deeper muscle tissue than the MOXY (maximum source:detector separation of 25 mm). Even in the absence of differences in the measurement algorithm (discussed later), one would therefore not necessarily expect identical muscle oxygen saturation values for the two systems.

While the two devices did provide similar values for male subjects, in female subjects, the PortaMon reported a lower resting TSI when compared with the MOXY. We showed that this difference appeared to be consequent to the gender difference in adipose layer. Optical density is greater in subjects with a thin layer of adipose tissue.[32] In SRS systems, the increased adipose layer results in a higher apparent %TSI in female subjects.[33] This effect is exaggerated in the MOXY. The smaller source:detector separation in the MOXY biases the light detected in favor of more surface tissues. It seems that the SR algorithm used is unable to completely correct for this effect. It is therefore even more important than usual in NIRS to measure and report on local body fat composition when using the MOXY, especially when comparing between subjects.

4.2 *Testing the Influence of External Pressure*

There were significant effects of the applied pressure on resting TSI, especially for the MOXY. At low external pressures (2 to 20 mmHg), the PortaMon reported a lower resting TSI (~8%) compared with the MOXY. As external pressure was increased above 20 mmHg, the difference between the two devices diminished. This difference was predominantly due to changes in the MOXY value, not the PortaMon. In particular, MOXY values showed a sharp decrease between 20 and 30 mm Hg. As external pressure is applied to the skins surface, arteriole, venule, and capillary intravascular hydrostatic pressure are equal in relation to the distance from the surface of the skin,[34] occluding the flow of blood to the periphery. As a larger proportion of light detected in the MOXY comes from surface tissue it is likely that the MOXY is more sensitive to pressure-induced changes in the dermis and subcutaneous oxygenation and blood flow. Again, the SR algorithm used to measure muscle TSI is less effective than the SRS method in the PortaMon in correcting for the effects of differences in blood flow and oxygenation in surface tissues. This finding has an important implication for researchers when undertaking repeated measures using the MOXY device, particularly when the removal and reapplication of the NIRS device is required. Furthermore, athletes using similar devices to inform training intensity should standardize the external pressure applied to hold the instrument in place.

4.3 *Test–Retest Reliability of Devices at Rest*

This is the first study to report reliability data of the MOXY device. In the current study, we report absolute [the similarity between repeated measures (CV)] reliability. Previous CV of

Table 4 Physiological responses during arm cranking and subsequent arterial occlusion.

	MOXY		PortaMon		*p* value
ATT (mm)			2.7 [1.6, 3.7]		
External pressure (mmHg)	10.8	[8.7, 13.0]	11.5	[9.5, 13.5]	0.6
TTE (s)	589.7	[538.1, 641.3]	584.7	[515.5, 653.8]	0.64
PPO (W)	97.85	[87.1, 108.6]	96.81	[82.4, 111.2]	0.64
Arterial occlusion					
Min (TSI)	12.9	[7.7, 17.9]	36.6	[28.7, 44.4]	<0.01**
Max (TSI)	87.2	[85.3, 89.0]	80.2	[77.4, 83.0]	<0.01**
Delta (TSI)	74.3	[68.9, 79.8]	43.7	[37.7, 49.7]	<0.01**
Baseline (resting)					
Raw (TSI)	61.5	[54.1, 68.9]	64.4	[60.9, 67.9]	0.34
Calibrated (%)	66.5	[55.0, 77.9]	63.6	[54.2, 73.0]	0.43
Incremental test					
Raw (Δ from baseline)					
0 W	−2.1	[−7.6, 3.5]	0.2	[−4.0, 5.4]	0.5
25 W	−9.6	[−14.4, −4.8]	−2.5	[−4.8, 9.3]	0.04*
50 W	−11.1	[−16.5, −5.7]	−5.6	[−10.4, 7.9]	0.12
75 W	−14.3	[−22.8, −5.8]	−8.3	[−16.2, 7.1]	0.09
100 W ($n = 3$)	−19.1	[−25.8, −12.5]	−12.3	[−23.8, −0.8]	0.22
Calibrated (Δ from baseline)					
0 W	−4.2	[−11.8, 3.5]	−0.3	[−14.6, 14.0]	0.55
25 W	−14.3	[−21.7, −7.0]	−6.9	[−24.5, 10.7]	0.27
50 W	−16	[−25.0, −7.0]	−13.9	[−26.2, −1.5]	0.74
75 W	−20.9	[−34.1, −7.6]	−19.1	[−31.5, −6.7]	0.8
100 W ($n = 3$)	−29.7	[−44.2, −15.3]	−25.8	[−44.4, −7.3]	0.59
Post ex. hyperemic max					
Raw	85.5	[80.4, 90.5]	80.7	[75.6, 85.9]	<0.01**
Calibrated	97.8	[93.0, 102.6]	101.3	[92.7, 109.8]	0.12

Note: ATT, adipose tissue thickness; TTE, time to exhaustion; PPO, peak power output.
*$P =< 0.05$
**$P =< 0.01$.

various NIRS monitors report resting TSI of the vastus lateralis between 2.3% and 5.8%.[25,35–37] These baseline TSI values are similar to that observed in the MOXY devices in our study (5.7% to 6.2%). Interestingly, the present CV for the PortaMon devices is lower than that previously reported 1.8% to 2.5% versus 4.7%.[25] However, this variation may be due to differences in the precise anatomical location the device is placed, leg position (supine versus seated), gender (male versus male and female), and health status of the participants (healthy versus chronic heart failure).

The acceptable test–retest reliability can be partially attributed to the homogeneous group of participants used in the present study, with an adipose layer of <7 mm. Therefore, caution is advised if using the devices on participants with greater adipose thickness and or when taking NIRS measures from an alternative anatomical location. Furthermore, small differences in ambient and muscular temperature may influence day-to-day variability,[4] as may slight changes in posture.[38] It is likely that in the present study, controlled environmental conditions,

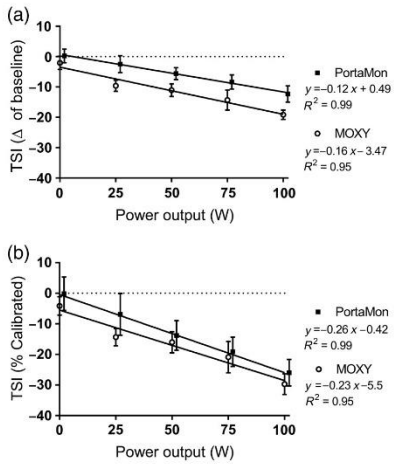

Fig. 4 (a) Relationship between power output and raw Δ TSI and (b) calibrated (%) values during incremental arm cranking (mean ± SEM).

abstinence of exercise between testing days and a supine body position attenuated the variance observed, contributing toward the very strong test–retest reliability of the devices.

Resting TSI values in the brain are used as threshold values for clinical hypoxia in SR devices such as the INVOS 5100C, EQUANOX Classic 7600, and FORE-SIGHT Elite[39] although this has been criticized given the differences in patient skull geometry and consequently light transport. In muscle, the InSpectra used second derivative spectroscopy to calculate a resting TSI in muscle that was suggested to report on tissue dysoxia in shock states.[40] This used the thenar (base of thumb) muscle due to the very small layers of overlaying adipose tissue in this area. In muscle groups more relevant to exercise physiologists and sports scientists, resting TSI values have been reported in calf muscle in compression clothing studies[38] and in the gastrocnemius during normobaric hypoxia.[41] When subjected to a normobaric hypoxic environment, the mean SRS-measured TSI change at rest, compared with the normoxic condition, was −2.5%. The authors report this finding to not statistically differ between conditions.

4.4 *Comparing Devices During Isometric Exercise*

There is no difference in ΔTSI between two models of the same device during isometric exercise. However, significant

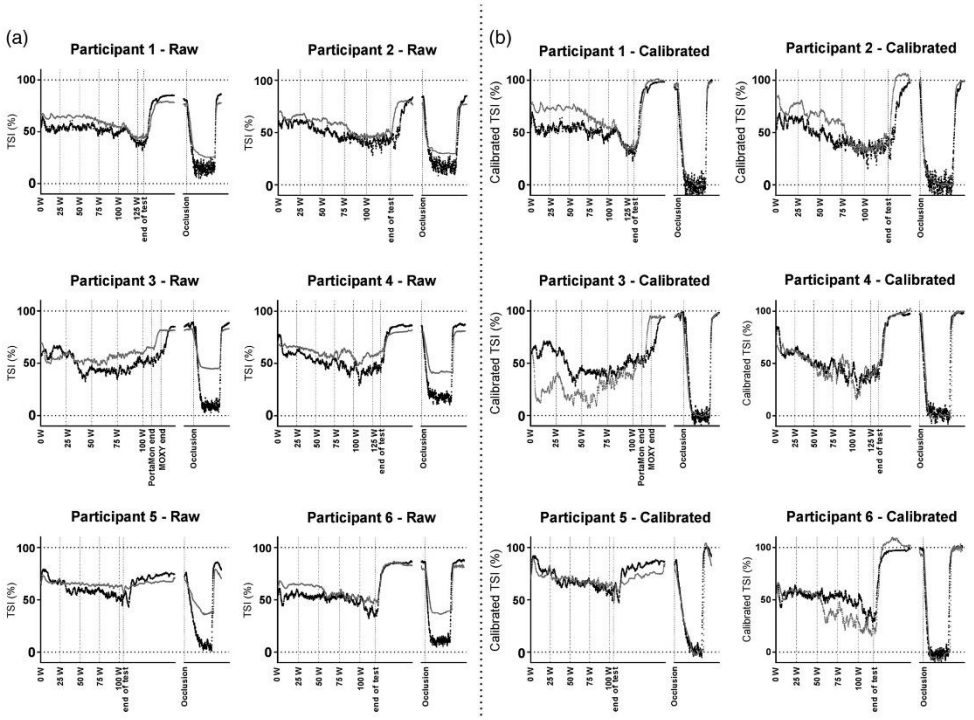

Fig. 5 (a) Individual participant TSI traces for raw and (b) calibrated values during arm cranking and arterial occlusion (MOXY = black line; PortaMon = gray line).

differences in ΔTSI are apparent when comparing MOXY versus PortaMon. The MOXY devices report a greater absolute ΔTSI change when compared with the PortaMon at both 30% and 50% MVC. The ΔTSI observed with the current PortaMon devices is similar to that of a previous study, also utilizing a PortaMon device,[8] reporting a ΔTSI reduction of ~6% and 11% from baseline at 30% and 50% MVC, respectively. Very few studies have utilized the MOXY device, however, of those available, the present ΔTSI at 30% MVC is similar to that observed in the gastrocnemius by supine individuals undertaking a plantar flexion exercise against a 6-kg weight (~37% versus ~38%).[42]

Both devices report appropriately that there is a decrease in muscle oxygenation during isometric exercise. However, unlike the situation for male subjects at rest, there are significant differences in the extent of desaturation observed during exercise. Is it possible to determine which one is likely to be "correct"? In one sense there is no single "correct" value as, given the differences in source:detector separation, the NIRS and PortaMon are reporting on different regions of the muscle (and having to correct for different amounts of surface tissue). However, some limits can be set by more invasive methods. Comparing oxygen saturation differences between femoral venous and radial arterial blood with the ΔTSI changes observed in the present study may identify whether one device is more comparable to direct methods than the other. In trained subjects, femoral venous oxygen saturations of 21% and arterial oxygen saturation of 96% were measured following maximal leg extensions.[43] Assuming the NIRS signal is an approximately equal contribution of arterial, capillary, and venous saturation, one would expect the absolute muscle oxygen saturation to be no lower than 55% in this case. Even allowing for the fact that femoral venous oxygen saturation represents the sum of all blood returning from the exercising leg, whereas the NIRS signal originates in the exercising muscle only,[44] the almost 60% drop in TSI in the MOXY device at only 50% MVC seems rather high. On the other hand, as has been noted,[45] the lack of a correction for the adipose layers can result in an underestimation of TSI changes using SRS methods. The variation between devices during the MVC exercise could be explained by the muscle contraction causing interference to the arterial inflow, therefore an increasing intramuscular pressure inducing ischemia. As such, the need to assess the devices during dynamic exercise provides an opportunity to understand the dynamic TSI range of the devices without the potential complication of ischemia.

4.5 *Comparing Devices During Dynamic Exercise*

During the incremental arm-cranking task, both NIRS devices demonstrated a continuous decline in TSI as power output increases until volitional fatigue. While some previous investigations have reported an early decline in muscle oxygen saturation during incremental arm exercise followed by a plateau at ~50% $\dot{V}O_{2\,max}$,[46] the general trend in TSI of the current study (Table 4) is closer to studies where the biceps brachii TSI progressively decreases throughout arm-cranking exercise.[5] Interestingly, the continuous decline in mean TSI at each stage of the test (Table 4), masked significant individual variation; in one person (participant 3) an increase in TSI was seen following the initial fall. The fact that both devices showed the same unusual trend lends confidence to the idea, that both this individual has differences in the balance between flow and metabolism as exercise proceeds and that both PortaMon and MOXY can detect this effect. By selecting participants and an anatomical location with very low ATT, and controlling external pressure at ~10 mmHg, variables previously identified to influence TSI values between devices were controlled. Nevertheless, we still observed a larger dynamic range in the study in the MOXY compared to the PortaMon.

4.6 *Comparing Devices During Occlusion/Reactive Hyperemia and the Effect of Physiological Calibration*

In an attempt to further explore the remaining differences, we performed a "physiological calibration" of the two devices, comparing the dynamic exercise data from the biceps brachii to an individual subject and machine-specific 0% to 100% range determined by a nominal 0% following arterial occlusion and a nominal 100% following the reactive hyperemia after that occlusion. During the arterial occlusion (Fig. 4), both devices fell to a fixed low level below baseline within the first 3 min following occlusion and both showed reactive hyperemia following cuff release with the TSI rising above baseline. This contrasts with a recent study measuring TSI following 3 min arterial occlusion comparing in older adult patients (66 ± 9 year) scheduled for elective coronary artery bypass grafting surgery.[22] In these older patients, 3 min occlusion was not enough to decrease TSI to a stable fixed baseline, probably due to a decrease in muscle oxygen consumption in this group compared to ours.

Despite choosing subjects groups with a similar baseline TSI, significant differences were seen in ischemia and reperfusion between the PortaMon and the MOXY. The range (hyperemia MAX minus occlusion MIN) in the PortaMon was Δ43.7% whereas in the same subjects the MOXY change was Δ74.3%. However, when calibrated against the physiological range observed during and postischemia, there is now no statistically significant difference among devices during the arm-crank exercise, nor the maximum value obtained during reactive hyperemia postexercise. This suggests that both methods are equally good at measuring muscle oxygenation changes in males with low ATT.

4.7 *Comparing Algorithms*

The PortaMon uses the well-established modified Beer–Lambert method for measuring changes in chromophore concentrations[47] and SRS for measuring absolute tissue oxygen saturation.[20] The MOXY uses Beer–Lambert and a proprietary SR algorithm based on a US patent.[48] Pathlength data are generated from a Monte Carlo Model, smoothed and used to generate a matrix of diffuse reflectance data at discrete values of tissue and sensor optical properties. This matrix is then used to convert the measured diffuse wavelength data to tissue optical properties, from which the oxygen saturation measure can be calculated. In their basic form, neither SRS nor SR algorithms take into account prior knowledge about individual differences in, for example, adipose layer thickness, resulting in some of the variability seen in this study. Some simple NIRS devices, such as the ASTEM NIR_{SRS}, have incorporated adipose layer measurements to improve the accuracy of their algorithms.[49] In principle, both PortaMon and MOXY methods described in this paper could make similar adjustments. Previous authors have incorporated ATTs of individual subjects as measured by ultrasound combined with SRS measurements in a two layer (adipose/muscle) Monte Carlo model to directly calculate muscle

μ_a.[45] A similar individualized measure should be possible for the MOXY device, decreasing the dependence of the TSI value on adipose layer thickness.

The MOXY device reports a significantly larger dynamic range when an arterial occlusion is applied, despite a shorter source:detector length when compared with the PortaMon. It has been suggested that the ischemic stimulus is more extensive in the muscle compared with the subdermal tissue;[16] therefore, the greater dynamic range reported by the MOXY may be related to the SR method enabling a greater muscle contribution than the SRS despite the smaller source:detector separation in the MOXY. However, it is also likely in part a function of algorithm optimization and specialization. The MOXY is designed to be used on muscle and could reasonably be expected to have been optimized for this system. The PortaMon, although designed to be used on muscle, makes no concessions or alterations to the basic SRS algorithm compared to similar Artinis devices used to measure brain function.

The minimum and maximum raw TSI values reported for the PortaMon (Δ43.7%) are similar to that previously reported for the NIRO 200-NX[22,50] following an arterial occlusion applied at the upper arm (Δ33%). This finding is unsurprising given that both the NIRO 200-NX and PortaMon both use SRS methods. However, the larger dynamic range reported by the MOXY (Δ74.3%) surpasses that of alternative SR devices such as the FORE-SIGHT elite (Δ46%) and INVOS5100C (Δ36%).[22] This illustrates the difficulty in comparing different SR devices, which use different algorithms and are likely sensitive to differences in the source:detector separation even when determining basic calibration ranges. The INVOS (3 and 4 cm) and FORESIGHT (2.5 and 5 cm) use significantly larger source:detector separations than the MOXY (1.2 and 2.5 cm) and, given their clinical interests, their algorithm development has likely focused more on brain than muscle measurements. However, in the absence of devices from these manufacturers with similar source:detector separations and the proprietary nature of the individual algorithms, it is impossible to speculate further at to the cause of these differences.

4.8 *Real World Applications*

The MOXY is designed to be of use to individuals in a variety of sporting environments. There have been suggestions as to how NIRS might be of use for individual athletes and coaches in, for example, tracking and optimizing training. However, in many cases, these have merely sought to mimic currently available tools, such as lactate thresholds, albeit with the benefit of being noninvasive.[51,52] Even then, differences in optical properties of individuals make these measurements unreliable in many cases.[53] No one has yet been able to demonstrate a specific benefit of using muscle NIRS to track training in an individual. What is required is a proper randomized trial comparing the use of NIRS to optimize training with current standard methods. The advent of relatively low-cost devices, such as the MOXY, makes such a trial more accessible. However, this work here suggests that, even if successful, the results of such a trial might remain specific for the NIR device used and not necessarily transferable to other spectrometers. This study has focused solely on the TSI values produced by the MOXY and PortaMon devices. Future studies could address the tHb values reported by the MOXY device and compare these with the (rarely reported) scaled tHb that can be derived from SRS methods.

Subcutaneous fat is known to have a large impact on NIRS signal. While high ATT results in less light absorption and therefore a stronger signal, the metabolically inactive fat tissue, coupled with lower hemoglobin levels will result in less signal change,[54] i.e., a blunted dynamic range. Given the observed influence of high ATT on resting TSI in the MOXY device and the small source:detector separation used, it is not clear how valid the current algorithm is for use in athletes with higher ATT; this includes a significant number of female athletes. In order to fully utilize the MOXY device in individuals with ATT > 7 mm, the source–detector distance should be increased accordingly. Commercial muscle NIRS devices with larger source–detection distances are widely available.[6] Future studies should measure TSI trend during dynamic exercise of those with ATT between 7 and 15 mm and determine whether the influence of ATT can be removed by applying an ischemic calibration as has been shown previously for muscle oxygen consumption measurements previously.[55]

5 Conclusion

This study shows that both MOXY and PortaMon devices produce acceptable TSI measures during supine rest and demonstrate a similar trend during dynamic exercise under appropriately controlled conditions in specific subject groups. During ischemia (arterial occlusion and isometric contractions), the MOXY device reports a greater raw dynamic range when compared with the PortaMon. However, by applying a physiological calibration following an arterial occlusion, the MOXY and PortaMon devices report similar changes from baseline during arm-crank exercise. Due to the limitations of calibrating NIRS, it is not possible to determine which device is a more accurate measure of absolute muscle oxygen saturation. Although, the PortaMon demonstrates a greater repeatability at rest, this may simply be reflective of the smaller dynamic range observed. The MOXY is marketed at athletes and coaches and priced accordingly (<£1000), whereas the higher priced PortaMon (<£10,000) tends to be used primarily by research scientists. For the researcher, the PortaMon has the advantage of measuring and reporting more NIRS parameters. At least in the case of vastus lateralis measurements, the PortaMon also appears to be less sensitive to variations in adipose layer thickness and applied external pressure. We recommend the application of the MOXY device primarily on individuals with a low ATT and that the external pressure applied to hold the device in place is either standardized upon each application or kept below 20 mmHg.

Disclosures

No conflicts of interest, financial or otherwise, are declared by the authors.

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