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

Submission Type: Original Article

Authors: Chris McManus[1], Prabhuraj D. Venkatraman[2], Gavin Sandercock[1],

Affiliations: [1]School of Sport, Rehabilitation and Exercise Sciences, University of Essex, Colchester, UK

[2]Manchester Fashion Institute, Manchester Metropolitan University, Manchester, UK

Corresponding Author: Chris J McManus, University of Essex, School of Sport, Rehabilitation and Exercise Sciences, Wivenhoe Park, CO4 3SQ, Essex, UK. Tel: +44 1206 874475. cmcman@essex.ac.uk

Running Title: The measurement of pressure applied by sports compression

Abstract word count: 150

Text only-word count: 3450

Number of figures and tables: 2 + 3

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 hosiery is applying relatively low levels of pressure, applicable to sports compression.

Keywords: pressure device, compression clothing, measurement and verification, bias, validity

Introduction

Compression garments 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 (Hill et al. 2014, Engel et al. 2016).

Despite the prospective benefits, little is known regarding the optimal 'interface-pressure' a compression garment should apply to a particular limb, to produce the greatest athletic benefit(Brophy-Williams et al. 2013). 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 (Partsch 2012). Unlike sports compression garments, 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 (Stout et al. 2012). 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 (Ménétrier et al. 2011) or values are provided by the garment manufacturer and are not directly measured (7). 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 compression garments 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 (Brophy-Williams et al. 2013).

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 (Partsch et al. 2006), 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.

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, covering the ankle to below the knee and full-length tights, covering the body from ankle to waist. The fabric properties of the two compression garments were investigated for performance including fabric weight using Sartorius balance. Fabric thickness was measured using a Shirley thickness gauge (Mitutoyo, Japan) (BS EN ISO 5084 1997). 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 (BS EN ISO 4294 1968) and 3 kg load was applied (Table 1). All fabrics were conditioned in standard laboratory conditions (20 ± 2°C, 65 ± 0% relative humidity) for 24 h prior to the fabric tests (BS EN ISO 139 2005). Garments did not undergo pre-treatment washing prior to or between measurements.

******Table 1 ******

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 387/1,2 (RAL-GZ 387/1 2008). The HOSY measures interface pressure (maximum resolution of 0.01 kPa), wear stretch (elongation %), tensile force (N/cm) and

residual pressure (%). The device (Figure 1) 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 (RAL-GZ 387/1 2008).

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' in published guidelines (Partsch et al. 2006) and standards (RAL-GZ 387/1 2008) was chosen as interface pressures exerted in this region are commonly cited in both medical (Mosti and Partsch 2013) and sports compression literature (Dascombe et al. 2011). 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.

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 (Fig 1.a) with the remaining garment placed in each fixed clamp rod (Fig 1.b). Once correctly fastened into the HOSY, the distance of location C (Fig 1.c) 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 hosiery so that all clamps reach this position simultaneously after 20 seconds (RAL-GZ 387/1 2008). 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 (Neumann et al. 2016, Nicolaides et al. 2018) 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 1 ******

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

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 (Thomas 2014).

Portable Device Protocols

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 inexpensive method making use of hydrostatic pressure.

As previously described (Brophy-Williams et al. 2013), 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 mmHg = b mmH_2O x [7.356×10^{-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.

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.

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.

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. Therefore, 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 (Bland and Altman 1986) 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), therefore providing bias values and upper and lower limits (± 1.96 SD). Difference was plotted as a function of the HOSY reference value (Krouwer 2008) 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 $\alpha = 0.05$.

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 2.

******Figure 2 ******

The interface pressures obtained by the reference standard, PicoPress and Kikuhime for the stockings and tights are shown in Table 2 and 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 2). The positive mean bias values for measures at the anterior and medial orientation (Table 2) show PicoPress produced systematically higher values when compared with the reference standard, Table 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 shows the between-device agreement for tights. When compared with the reference standard, the PicoPress (Table 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 2 ******

******Table 3 ******

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 (Van den Kerckhove et al. 2007, Brophy-Williams et al. 2013, Chassagne et al. 2015) we confirmed the Kikuhime and PicoPress devices produced reliable in-vitro measures of hydrostatic pressure (Figure 2). 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 (Thomas 2014). 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 similar to that previously reported, in that interface pressure at the anterior orientation of the lower leg is greatest (Veraart et al. 1997, Liu et al. 2006, Rong et al. 2007). 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 compression garment is inversely proportional to the radius of curvature at a given location. It therefore 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 (Mosti and Rossari 2008). The Kikuhime systemic overestimation of interface pressure may misclassify compression hosiery. . However, at 30 – 50 mmHg both devices reported accurate and matching values (Mosti and Rossari 2008). The validity of devices at lower pressures is important when assessing sports compression garments which typically produce interface pressures of ~10 – 30 mmHg (Beliard et al. 2015, Hill et al. 2015). 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 (Vinckx et al. 1990).

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.

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. Future research should compare the interface pressure reported by portable pressure devices with compression garments 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.

The PicoPress and Kikuhime are commonly cited devices in medical literature (Mosti et al. 2009, Schuren et al. 2010), sub-bandage pressure assessment (Mosti and Partsch 2010,

Weller et al. 2010), and as reference devices in the development of piezoresistive sensors (Chi et al. 2017). However, in the current study, and in agreement with previous research (Mosti and Rossari 2008, Partsch and Mosti 2010, Thomas 2014), 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.

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 hosiery is applying relatively low levels of pressure, applicable to sports compression.

Acknowledgements

We would like to thank Sarah Steinbeck for her assistance with the HOSY data collection and Mike Green for support received in the use of Hounsfield tensile strength kit from School of Engineering, Manchester Metropolitan University, Manchester, UK.

Conflict of interest

The authors have no conflicts of interest

References

Beliard S, Chauveau M, Moscatiello T, *et al.* Compression garments and exercise: no influence of pressure applied. *J. Sports Sci. Med.* (2015); **14**: 75.

Bland JM, Altman D. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* (1986); **327**: 307–310. https://doi.org/10.1016/s0140-6736(86)90837-8

Brophy-Williams N, Driller MW, Halson SL, *et al.* Evaluating the Kikuhime pressure monitor for use with sports compression clothing. *Sport. Eng.* (2013); **17**: 55–60. https://doi.org/10.1007/s12283-013-0125-z

BS EN ISO 139. British Standards Institution. (2005). 139: Textiles. Standard atmospheres for conditioning and testing. Milton Keynes. BSI. 2005

BS EN ISO 4294. British Standards Institution . (1968). 4294: Textiles, Method of test for stretch and

recovery of fabrics. Milton Keynes: BSI. 1968

BS EN ISO 5084. British Standards Institution . (1997). 5084: Textiles. Determination of thickness of textiles and textile products. Milton Keynes: BSI. 1997

Chassagne F, Martin F, Badel P, *et al.* Experimental investigation of pressure applied on the lower leg by elastic compression bandage. *Ann Biomed Eng* (2015); **43**: 2967–2977. https://doi.org/10.1007/s10439-015-1352-1

Chi Y-W, Tseng K-H, Li R, *et al.* Comparison of piezoresistive sensor to PicoPress® in in-vitro interface pressure measurement. *Phlebology* (2017);315–320. https://doi.org/10.1177/0268355517705292

Dascombe BJ, Hoare TK, Sear JA, *et al.* The effects of wearing undersized lower-body compression garments on endurance running performance. *Int J Sport. Physiol Perform* (2011); **6**: 160–173. https://doi.org/10.1123/ijspp.6.2.160

Engel FA, Holmberg H-C, Sperlich B. Is there evidence that runners can benefit from wearing compression clothing? *Sport. Med* (2016); **46**: 1939–52. https://doi.org/10.1007/s40279-016-0546-5

Hill J, Howatson G, van Someren K, *et al.* Compression garments and recovery from exercise-induced muscle damage: a meta-analysis. *Br J Sport. Med* (2014); **48**: 1340–1346. https://doi.org/10.1136/bjsports-2013-092456

Hill JA, Howatson G, van Someren KA, *et al.* The variation in pressures exerted by commercially available compression garments. *Sport. Eng.* (2015); **18**: 115–121. https://doi.org/10.1007/s12283-015-0170-x

Van den Kerckhove E, Fieuws S, Massage P, *et al.* Reproducibility of repeated measurements with the Kikuhime pressure sensor under pressure garments in burn scar treatment. *Burns* (2007); **33**: 572–578. https://doi.org/10.1016/j.burns.2006.08.032

Krouwer JS. Why Bland–Altman plots should use X, not (Y+ X)/2 when X is a reference method. *Stat. Med.* (2008); **27**: 778–780. https://doi.org/10.1002/sim.3086

Liu R, Kwok Y-L, Li Y, *et al.* A three-dimensional biomechanical model for numerical simulation of dynamic pressure functional performances of graduated compression stocking (GCS). *Fibers Polym.* (2006); **7**: 389–397. https://doi.org/10.1007/bf02875771

Ménétrier A, Mourot L, Bouhaddi M, *et al.* Compression sleeves increase tissue oxygen saturation but not running performance. *Int J Sport. Med* (2011); **32**: 864–868. https://doi.org/10.1055/s-0031-1283181

Mosti G, Mattaliano V, Arleo S, *et al.* Thigh compression after great saphenous surgery is more effective with high pressure. *Int. Angiol.* (2009); **28**: 274.

Mosti G, Partsch H. Inelastic bandages maintain their hemodynamic effectiveness over time despite significant pressure loss. *J. Vasc. Surg.* (2010); **52**: 925–931. https://doi.org/10.1016/j.jvs.2010.04.081

Mosti G, Partsch H. Occupational leg oedema is more reduced by antigraduated than by graduated stockings. *Eur J Vasc Endovasc Surg* (2013); **45**: 523–527. https://doi.org/10.1016/j.ejvs.2013.01.032

Mosti G, Rossari S. The importance of measuring sub bandage pressure and presentation of new measuring device. *Acta Vulnol* (2008); **6**: 31–36.

Neumann HA, Partsch H, Mosti G, *et al.* Classification of compression stockings: report of the meeting of the International Compression Club, Copenhagen. *Int. Angiol. a J. Int. Union Angiol.* (2016); **35**: 122–128.

Nicolaides A, Kakkos S, Baekgaard N, *et al.* Management of chronic venous disorders of the lower limbs. Guidelines According to Scientific Evidence. Part I. *Int. Angiol. a J. Int. Union Angiol.* (2018); **37**: 181.

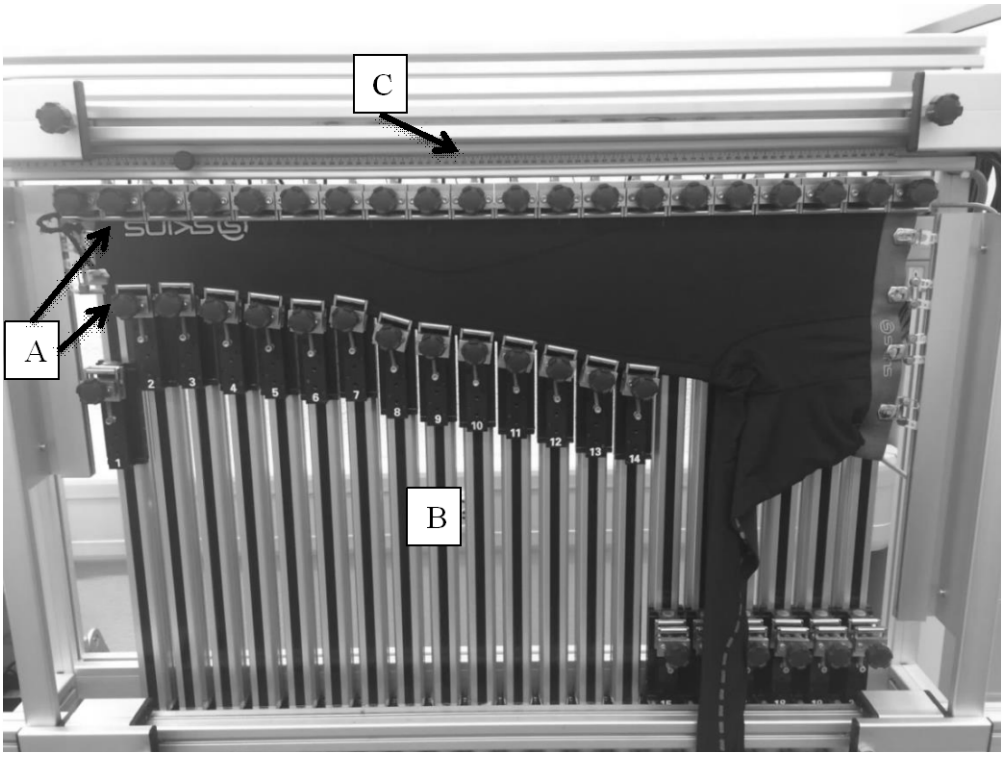
Partsch H. Compression therapy: clinical and experimental evidence. *Ann Vasc Dis* (2012); **5**: 416–422. https://doi.org/10.3400/avd.ra.12.00068

Partsch H, Clark M, Bassez S, *et al.* Measurement of lower leg compression in vivo: recommendations for the performance of measurements of interface pressure and stiffness.

446 *Dermatol Surg* (2006); **32**: 224–233. https://doi.org/10.1111/j.1524-4725.2006.32039.x
447 Partsch H, Mosti G. Comparison of three portable instruments to measure compression pressure. *Int*
448 *Angiol* (2010); **29**: 426–430.
449 RAL-GZ 387/1. Medical compression hosiery. Deutsches institut für gütesicherung und
450 kennzeichnung. Berlin: E.V. Beuth Verlag; January 2008. 2008
451 Rong L, Lin KY, Yi L, *et al.* Skin pressure profiles and variations with body postural changes beneath
452 medical elastic compression stockings. *Int. J. Dermatol.* (2007); **46**: 514–523.
453 https://doi.org/10.1111/j.1365-4632.2007.03175.x
454 Rugg S, Sternlicht E. The effect of graduated compression tights, compared with running shorts, on
455 counter movement jump performance before and after submaximal running. *J Strength Cond*
456 *Res*, 2012/06/14. (2013); **27**: 1067–1073. https://doi.org/10.1519/JSC.0b013e3182610956
457 Schuren J, Vos A, Allen JO. Venous leg ulcer patients with low ABPIs: How much pressure is safe and
458 tolerable? *EWMA J.* (2010); **10**
459 Stout N, Partsch H, Szolnoky G, *et al.* Chronic edema of the lower extremities: international
460 consensus recommendations for compression therapy clinical research trials. *Int Angiol*,
461 2012/07/18. (2012); **31**: 316–329.
462 Thomas S. Practical limitations of two devices used for the measurement of sub-bandage pressure:
463 Implications for clinical practice. *J Wound Care* (2014); **23**: 300–313.
464 https://doi.org/10.12968/jowc.2014.23.6.300
465 Veraart JCJM, Pronk G, Neumann HA. Pressure differences of elastic compression stockings at the
466 ankle region. *Dermatol Surg* (1997); **23**: 935–939. https://doi.org/10.1111/j.1524-
467 4725.1997.tb00753.x
468 Vinckx L, Boeckx W, Berghmans J. Analysis of the pressure perturbation due to the introduction of a
469 measuring probe under an elastic garment. *Med. Biol. Eng. Comput.* (1990); **28**: 133–138.
470 https://doi.org/10.1007/bf02441768
471 Weller CD, Jolley D, McNeil J. Sub-bandage pressure difference of tubular form and short-stretch

compression bandages: in-vivo randomised controlled trial. *Wound Pract. Res. J. Aust. Wound Manag. Assoc.* (2010); **18**: 100.

Figure 1. The Hohenstein System (HOSY) showing (a) clamps holding the bottom of the garment, (b) 20 measuring rods with clamps and (c) measurement tape.



485

486

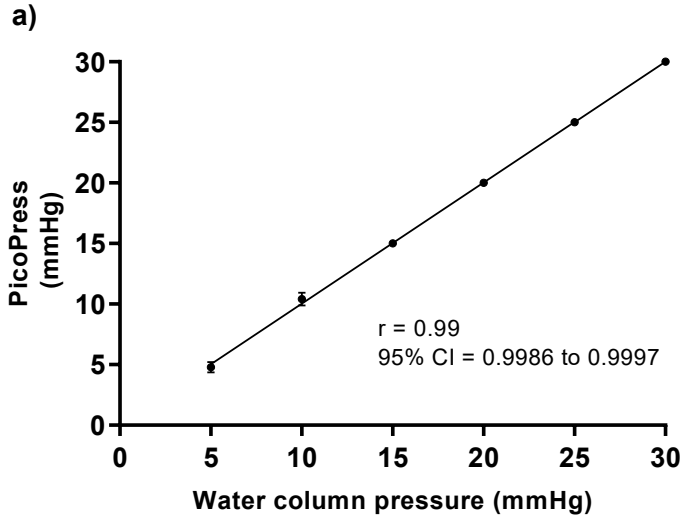
487

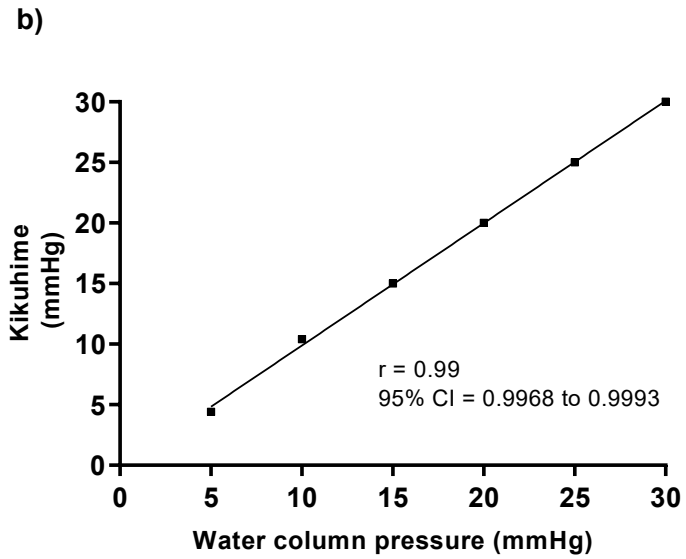
488

489

490 **Figure 2.** Linearity and correlation coefficients for the (a) PicoPress and (b) Kikuhime

491 device.





492

493

494

495

496

497

498

499 **Table 1.** Fabric characteristics of the compression garments.

500

	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

501

502

503

504

505 **Table 2**. Interface pressure, significance, agreement values (bias and limits) and slope

506 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]
$\overline{x}$	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
$\overline{x}$	29.4 [2.5]	<0.01	-9.2 [-14.6; -3.9]	1.1 [-0.5 – 2.7]

$\overline{x}$ = 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. 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]
$\overline{x}$	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]
$\overline{x}$	16.8 [2.1]	<0.01*	-3.7 [-8.1; 0.7]	0.8 [-1.2 – 2.8]

$\overline{x}$ = 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.

511