

Evaluating the Kikuhime pressure monitor for use with sports compression clothing

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Abstract Reporting accurate and reliable measures of pressure exerted by sport compression clothing assists in the interpretation and comparison of study findings. The objective of the current study was to assess the validity and reliability of the Kikuhime pressure monitoring device to measure the pressure of sport compression garments. To assess validity, three separate Kikuhime sensors were compared to known pressures inside a water column, at 5 mmHg increments ranging from 5 to 100 mmHg. Intra- and inter-tester reliability was determined by comparing the results of two individuals performing five interface pressure measures at six different landmarks across the lower and upper leg of an athlete wearing sports compression leggings. All three sensors tested exhibited a very high intra-class correlation with the reference value (mean ICC = 0.996). The typical error of measurement was low for both intra- and inter-tester reliability (mean \pm SD: 1.3 ± 0.9 and 1.8 ± 0.9 mmHg, respectively). These results expressed as a coefficient of variation were 4.9 ± 2.4 and 7.4 ± 5.4 %, respectively. The findings from the current study suggest that the Kikuhime device is a valid and reliable instrument for use in situ when measuring the pressure of sports compression garments in athletes assuming a static standing posture. The instrument could be used in future research involving compression

garments to accurately quantify interface pressures and their subsequent effect on physiological and/or performance measures.

Keywords Interface pressure · In situ · Reliability · Validity

1 Introduction

The use of compression garments and compression bandaging has been well documented in the medical literature as a method of treating circulatory and lymphatic disorders [1]. Given the efficacy of compression garments as a treatment in the medical field, the use of compression garments in the athletic industry has become increasingly popular over the past decade, with several commercial companies claiming that the associated medical benefits can be applied to enhance both recovery and performance in an exercise setting [2]. A substantial number of research papers have been published in both settings; however, most exhibit a limitation in that they do not report interface pressure applied by the compression garments [3]. Many papers have merely relied on manufacturers' fitting recommendations and pressure application guidelines to estimate interface pressure levels [4–6].

The reporting of interface pressure would enhance interpretation of research findings, assist in substantiating manufacturers' claims of pressures exerted, and provide a greater understanding of garment pressure, which has the potential to be highly variable between individuals. Interface pressure measurement would also enhance future research undertaken into compression, enabling the investigation of optimal pressure gradients required for sports compression garments to improve recovery.

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If researchers are to report interface pressure measurements, a valid and reliable pressure monitoring device should be used, alongside a standardised testing protocol. Several different systems have previously been assessed [7], with the Kikuhime pressure monitoring device (MediGroup, Melbourne, Australia) reported to be valid and reliable [7–9]. Various methods have been utilised to assess the validity of the Kikuhime device. Flaud et al. [7] placed the sensor in a pressurised chamber, where the pressure of the chamber was measured using a different pressure sensor that had previously been calibrated with a water column. The authors concluded that the device had an overall error of 4.3 %. Van den Kerckhove et al. [8] connected the Kikuhime pressure sensor to a water column to compare pressure readings, reporting a linear relationship between the two measures up to a pressure of 30 mmHg. Experimental trials undertaken by Partsch and Mosti [9] involved the sensor being placed between a rigid cylinder and an inflatable blood pressure cuff connected to a mercury manometer, as well as an in situ measurement involving a human limb for the same procedure. The authors declared the device to be accurate, with a coefficient of variation (CV) of 4.17 % within the tested range on the human limb. However, their results showed a high pressure variation for pressures below 30 mmHg.

Two of the aforementioned papers also investigated the Kikuhime device's reliability. Flaud et al. [7] noted the importance of re-creating in situ measurement as closely as possible for these measurements, but chose not to use a human limb due to the high likelihood of its variability influencing results. Rather, a cylindrical model leg with a constant curvature was used to gather data on repeated measures. Flaud et al. [7] reported favourably on the repeatability of the device, with the standard deviation (SD) of repeated measures less than 0.6 mmHg and the CV between 2 and 3.5 %. Although there are difficulties in using a human limb to assess reliability, it is critical that in situ measurements be taken so that reliability of the device can be tested in a practical setting, as this is the intended use of the sensor.

Studies involving the Kikuhime device are yet to quantify the intra-tester and inter-tester reliability of the instrument when measuring in situ interface pressure of compression garments on uninjured skin on the lower limb. This information is of particular relevance to further studies investigating the use of lower limb sports compression garments, as previous validity and reliability of the Kikuhime device relates to conditions of burns, venous ulcers or other medical complications. The aims of the current study were two-fold: to determine the validity of the Kikuhime device by comparing it directly to a “gold standard” across a range of pressures, and to determine the inter- and intra-tester reliability when using the Kikuhime

device to measure sport compression garments over six landmarks on an athlete.

2 Methods

2.1 The Kikuhime pressure monitoring device

The Kikuhime pressure monitoring device consists of a pressure transducer connected to a detachable 70 cm length of silicon tubing, which attaches to an oval-shaped polyurethane sensor (30 × 38 mm). Inside the sensor is a 3-mm-thick sheet of polyurethane foam. The pressure exerted on the balloon is directly transmitted to the transducer and continuously displayed in real time in 1 mmHg increments.

The device was tested in a temperature-controlled laboratory (22.4 ± 0.3 °C). Two methods were used to evaluate the performance of the sensor, first for validity, and then for intra-tester and inter-tester reliability in situ.

2.2 Water column (gold standard measure used for validity)

The pressure sensor was placed at the bottom of a 160-cm-tall clear cylindrical container. A steel measuring tape was attached to the outside of the cylinder, before it was filled to predetermined levels with de-ionised water. The water's temperature was measured with a TM50 thermometer (Temp-Seeker, FL, USA) so as to determine the density of the water. The water's density dictated the water depths selected so as to apply interface pressures from 5 to 100 mmHg to the sensor, in 5 mmHg increments. The depth of water required to produce these pressures was calculated using the equation [10],

$$a \text{ mmHg} = b \text{ mmH}_2\text{O} \times [7.35559135 \times 10^{-2}]$$

Depth measurements were taken as the distance between the lowest point of the water's meniscus and the centre of the pressure sensor. Repeat measurements for three separate detachable sensors were recorded at each depth/pressure. At the time of testing, all sensors were new and unused.

2.3 Measurements in situ (intra- and inter-tester reliability)

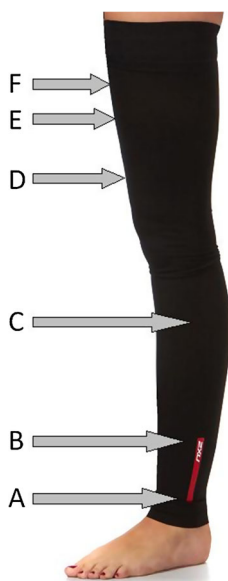
A well-trained male endurance runner (height 1.86 m, body mass 71.0 kg, sum of 7 skinfolds 35.1 mm) signed an informed consent document approved by the Australian Institute of Sport and University of Tasmania Ethics Committees before being fitted with sports compression

leggings (2XU compression leg sleeves, Victoria, Australia). The pressure sensor was positioned on the lower right leg prior to the leggings being worked up the legs so that the lower edge of the cuff on the ankle of the garment aligned with the distal border of the medial malleolus. The sensor was then aligned to measure pressure at six different landmarks along the leg.

The landmarks were positioned 5 cm proximal to the distal border of the medial malleolus (a), 5 cm proximal to a (b), on the medial aspect of the maximal calf girth (c), on the anterior aspect of the thigh 10 cm below landmark e (d), the mid-point between the inguinal crease and the superior-posterior border of the patella (e) and 5 cm proximal to landmark e (f) (Fig. 1). Landmarks were chosen based on previous research investigating sports compression garments [11, 12] and the commonly used European Standards for testing compression in medical hosiery [13–15].

The pressure exerted at each of these landmarks was measured while the participant was standing with their feet shoulder-width apart and their weight evenly distributed. Following the completion of these measurements, the leggings were removed and the procedure repeated by another researcher. This process was carried out five times by each researcher (ten measurements per site). The same pair of leggings was used throughout the testing protocol following the results of pilot testing in our laboratory that reported the maintenance of interface pressure for at least 15 wears from new (unpublished observations). Landmarks were palpated by the experimenter and marked with a pen. Marks were removed with an alcohol swab between trials so as to further reduce the possibility of experimenter bias. A third party was responsible for reading and recording measurements on the Kikuhime device.

Fig. 1 Landmarks *a* (5 cm proximal to the distal border of the medial malleolus), *b* (5 cm proximal to *a*), *c* (medial aspect of the maximum calf girth), *d* (anterior aspect of the thigh, 10 cm below *e*), *e* (the mid-point between the inguinal crease and the superior-posterior border of the patella) and *f* (5 cm proximal to *e*), where interface pressure measurements were taken



2.4 Data analysis

An intra-class correlation (ICC) was used to analyse the validity of the Kikuhime device, by comparing sensor readings to reference values.

Accuracy was evaluated using the global error calculation [16],

$$\text{Global error} = \text{Average} \left| \frac{P - P_{\text{ref}}}{P_{\text{ref}}} \right|$$

where P is the measured pressure and P_{ref} is the reference pressure.

Systematic errors were analysed by calculating the bias, using the Bland and Altman approach [17].

$$\text{Bias} = d \pm 2s$$

where d is the mean and s is the standard deviation of $P - P_{\text{ref}}$

Intra- and inter-tester reliability was assessed via the calculation of typical error of measurement (TEM) [18]. TEM was calculated as:

$$\text{TEM} = \text{SD} \times \sqrt{2}$$

where SD is the standard deviation of measures at each site. CV was calculated from the TEM so that it could be expressed as a percentage change, removing the tendency for larger values to report a more substantial TEM [19]. These analyses were performed using Microsoft Excel software (Microsoft Office Excel 2007, Redmond, WA, USA). Data are presented as mean \pm SD.

3 Results

3.1 Validity of the Kikuhime device

Results from the validity analysis of the Kikuhime device are presented in Table 1. All three sensors tested exhibited a very strong correlation with the reference value (mean ICC = 0.996). Global error was calculated to have a mean value of 2.97 % across the three sensors. This consisted of a mean bias (systematic error) of 2.28 % and a random error of 0.69 %.

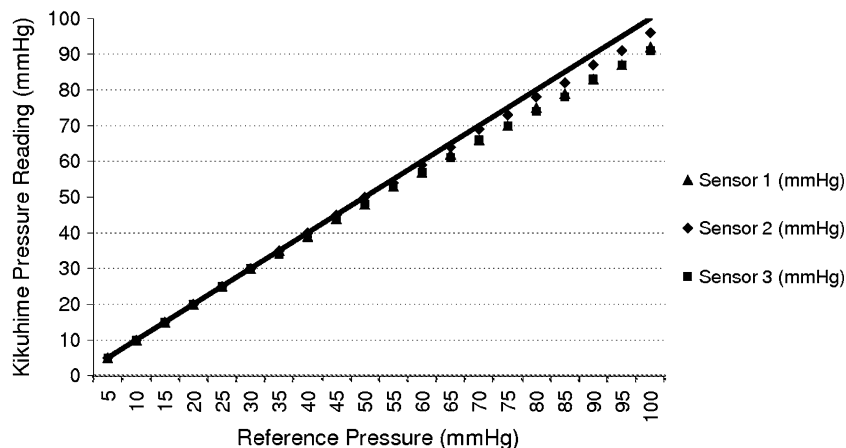
Figure 2 displays the differences between the reference pressure values and those displayed by the Kikuhime device. Perfect accuracy was displayed by all sensors up to a pressure of 35 mmHg.

3.2 Measurements in situ of intra-tester reliability

Table 2 exhibits the TEM and CV for both the intra- and inter-tester reliability of the Kikuhime device. The mean TEM for the five sets of recordings across the six

Table 1 Intra-class correlation, global error, bias and coefficient of variation for the three Kikuhime sensors

	Intra-class correlation	Global error (%)	Bias	Random error (%)	Coefficient of variation (%)
Mean	0.996 ± 0.002	2.97 ± 2.67	2.28 ± 2.44	0.69 ± 0.23	1.11 ± 0.15

Fig. 2 Comparison of the reference pressure with the measurements recorded by the Kikuhime device (reference pressure denoted by *black line*)**Table 2** Mean pressure, typical error of measurement (TEM) and coefficient of variation (CV) calculated from the intra-tester and inter-tester reliability analysis

	Site A	Site B	Site C	Site D	Site E	Site F	Mean
Mean pressure (mmHg)	22.2 ± 2.7	29.8 ± 2.3	32.4 ± 3.7	17.6 ± 1.9	22.9 ± 0.9	24.6 ± 1.1	
Intra-tester							
Mean TEM	1.1 ± 1.5	1.1 ± 1.6	3.0 ± 4.2	0.6 ± 0.9	0.9 ± 1.3	0.9 ± 1.3	1.3 ± 0.9
Mean CV	4.5 ± 6.4	3.7 ± 5.3	9.8 ± 14.1	3.6 ± 5.1	4.2 ± 6.0	3.8 ± 5.5	4.9 ± 2.4
Inter-tester							
Mean TEM	2.7 ± 3.8	2.6 ± 3.6	2.3 ± 3.3	1.9 ± 2.7	0.8 ± 1.1	0.6 ± 0.8	1.8 ± 0.9
Mean CV	13.3 ± 19.3	8.9 ± 12.8	7.7 ± 11.0	12.4 ± 18.0	1.0 ± 4.8	1.0 ± 3.4	7.4 ± 5.4

TEM typical error of measurement (mmHg), CV coefficient of variation (%)

landmarks used for intra-tester reliability was 1.3 ± 0.9 mmHg, with a CV of 4.9 ± 2.4 %.

3.3 Measurements in situ of inter-tester reliability

Inter-tester analysis across the six sites resulted in a mean TEM of 1.8 ± 0.9 and mean CV of 7.4 ± 5.4 % (Table 2).

4 Discussion

This is the first study to assess the reliability and validity of the Kikuhime device in situ on an athlete wearing sports compression garments. The results from the current study show the Kikuhime to be a valid and reliable device that can be used to measure pressure gradients of compression garments on uninjured skin. The Kikuhime device exhibited a very strong intra-class correlation when compared to a reference value

(ICC = 0.996), and displayed a low TEM when analysed for intra- and inter-tester reliability in situ (TEM = 1.3 ± 0.9 mmHg and 1.8 ± 0.9 mmHg, respectively), as would be required to investigate compression clothing.

Previous studies have assessed the Kikuhime's validity with favourable outcomes [7–9]. However, the studies have each included possible sources of error by comparing the Kikuhime device's measurements to other devices or non-validated techniques. This study is the first to assess the Kikuhime device by immersing the sensor under a column of water, which is thought to provide a “gold standard” method of validation. The strong ICC (0.996) supports the results by previous investigations that have demonstrated the Kikuhime to be a valid instrument [7, 9]. The current study adds to the literature by comparing the Kikuhime device to a large range of pressures, while most other papers have limited investigated pressures to a maximum of 30 mmHg [7, 8].

Investigating beyond these bounds allowed the device's limitations to be detailed more clearly. The results of the current study are in stark contrast to those produced by Partsch and Mosti [9], which detailed the largest differential between the reference value and the Kikuhime device at pressures below 30 mmHg, whereas this was the most accurate range for the current investigation. A plausible explanation for this difference would be that the reference value (blood pressure cuff) used in Partsch and Mosti's [9] experiment applied an uneven pressure on the Kikuhime sensor surface due to deformation of the cuff, particularly at lower pressures. The disagreement may also explain the difference in CV between the two studies, with the current study producing a lower CV of 1.11 %, while Partsch and Mosti [9] reported a CV of 4.17 %. Similar comparisons are apparent when the global error of the current findings are assessed against that reported by Flaud et al. [7] (global error = 4.30 %), with a lower value reported in the current study (global error = 2.97 %). Again, the value of using a direct assessment method must be recognised in this situation as it assists in reducing possible sources of error. Further to these results, Flaud et al. [7] reported a bias similar to that of the present study (-1.4 ± 2.0), suggesting that random errors contributed to the greater global error reported by their study. It must be noted that the current study assessed the Kikuhime's validity under constant environmental conditions (22.4 ± 0.3 °C), and therefore results can only be interpreted within these parameters, and not extrapolated to encompass differing ambient temperature conditions. The study did not assess the Kikuhime device's sensitivity to mechanical hysteresis either, and this may influence the accuracy of repeated measurements [3].

The intra-tester TEM of $1.3 (\pm 0.9)$ was particularly low, especially considering the 1 mmHg resolution of the Kikuhime device and the wide range of pressure measurements exhibited in Table 2. TEM was regarded as a more pertinent measure than CV for the Kikuhime device, as CV was skewed by this low resolution. Similar results were reported by Van den Kerckhove et al. [8], who assessed intra-tester reliability by means of repeated measures on a plastic cylinder and reported a TEM of 1.46 mmHg. These values suggest strong intra-tester reliability when trained personnel use the Kikuhime device according to a specific protocol.

Inter-tester reliability in the current study returned a higher TEM and CV than intra-tester reliability (1.3 ± 0.9 mmHg and 4.9 ± 2.4 %, as opposed to 1.8 ± 0.9 mmHg and 7.4 ± 5.4 %, respectively). Values were similar to those reported by Van den Kerckhove et al. [8] (TEM = 1.89 mmHg). The sensitivity of the device to 1 mmHg further strengthens the credibility of these values representing a reliable instrument.

In conclusion, the Kikuhime pressure monitoring device is a valid and reliable tool, exhibiting a global error of just 2.97 % and intra- and inter-tester reliability TEM of 1.3 ± 0.9 and 1.8 ± 0.9 mmHg, respectively, when assessed on an athlete assuming a standing posture. The instrument proved to be extremely accurate to 35 mmHg. With the majority of interface pressure measurements falling within this range, the Kikuhime is a suitable instrument for use in research studies involving sports compression garments in situ. It is important to acknowledge that the Kikuhime device may be sensitive to temperature and hysteresis, and therefore the findings of this study are limited to the environmental conditions under which the sensors were assessed.

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References

1. MacRae BA, Cotter JD, Laing RM (2011) Compression garments and exercise: garment considerations, physiology and performance. *Sports Med* 41:815–843
2. Driller MW, Halson SL (2013) The effects of wearing lower-body compression garments during a cycling performance test. *Int J Sports Physiol Perform* 8:300–306
3. Partsch H, Clark M, Bassez S, Benigni JP, Becker F, Blazek V, Caprini J, Cornu-Thenard A, Hafner J, Flour M, Junger M, Moffatt C, Neumann M (2006) Measurement of lower leg compression in vivo: recommendations for the performance of measurements of interface pressure and stiffness: consensus statement. *Dermatol Surg* 32:224–232
4. Davies V, Thompson KG, Cooper SM (2009) The effects of compression garments on recovery. *J Strength Cond Res* 23: 1786–1794
5. Duffield R, Portus M (2007) Comparison of three types of full-body compression. *Br J Sports Med* 41:409–414
6. French DN, Thompson KG, Garland SW, Barnes CA, Portas MD, Hood PE, Wilkes G (2008) The effects of contrast bathing and compression therapy on muscular performance. *Med Sci Sports Exerc* 40:1297–1306
7. Flaud P, Bassez S, Counord JL (2010) Comparative in vitro study of three interface pressure sensors used to evaluate medical compression hosiery. *Dermatol Surg* 36:1930–1940
8. Van den Kerckhove E, Fieuws S, Massage P, Hierner R, Boeckx W, Deleuze JP, Laperre J, Anthonissen M (2007) Reproducibility of repeated measurements with the Kikuhime pressure sensor under pressure garments in burn scar treatment. *Burns* 33: 572–578
9. Partsch H, Mosti G (2010) Comparison of three portable instruments to measure compression pressure. *Int Angiol* 29:426–430
10. Lide DR, Frederikse HPR (1996) CRC handbook of chemistry and physics: a ready-reference book of chemical and physical data, 77th edn. CRC Press, Boca Raton
11. Troynikov O, Ashayeri E (2011) 3D body scanning method for close-fitting garments in sport and medical applications. HFESA 47th Annual Conference, Crows Nest, pp 11–16
12. Troynikov O, Ashayeri E, Burton M, Subic A, Alam F, Marteau S (2010) Factors influencing the effectiveness of compression garments used in sport. *Procedia Eng* 2:2823–2829

13. Partsch H, Partsch B, Braun W (2006) Interface pressure and stiffness of ready made compression stockings: comparison of in vivo and in vitro measurements. *Am Venous Forum Miami* 44:809–814
14. Stolk R, Wegen van der-Franken CP, Neumann HA (2004) A method for measuring the dynamic behavior of medical compression hosiery during walking. *Dermatol Surg* 30:729–736
15. European Committee for Standardization (2009) Method for testing compression in medical hosiery. Estonia, pp 6–7
16. Polliack AA, Sieh RC, Craig DD (2000) Scientific validation of two systems of pressure sensors marketed for adjustment of compression stockings. *J Orthop* 3:318–327
17. Bland JM, Altman DG (1986) Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1:307–310
18. Hopkins WG (2012) Analysis of reliability with a spreadsheet (Excel spreadsheet). *Sportscience*. <http://www.sportsci.org/resource/stats/>
19. Pyne D (2012) *Physiological tests for elite athletes*, 2nd edn. Human Kinetics, Champaign