Evaluating compression variation for seamless knitted fabrics: an experimental study using Kikuhime sensors

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Background. Scientific knowledge about compression garments, such as sport bras, is necessary due to the established detrimental health effects caused by wearing the wrong size compressive garments (Miyatsuji et al., 2002). The compression exerted on the breasts can be engineered by adjusting the material properties, particularly the yarn and knitting structures. Maleki et al. (2011) showed that the knitted stitch length and strain percent are important factors affecting the garment's pressure on the body, and the repeated washing had a significant effect on the pressure reduction of knitted fabrics. Seamless knitting via circular knitting machines has been the primary technology used for manufacturing compression sport bras, creating fine-knitted fabrics via micro-denier size yarns (Lau & Yu, 2016). These machines can create complex knitted fabric structures by combining jersey, tuck, or float stitches in each row, while also combining multiple yarn types, such as Nylon, polyester, cotton, wool and spandex. Moreover, the plain plating feature allows the separation of yarns from front to back of knitted structures, creating fabrics with special moisture management properties (Lau & Yu, 2016). Variations in loop length and yarn tension among others have been found to significantly influence the moisture transport properties of the fabrics as well as their compression properties (Öner & Okur, 2013; Liu & Hu, 2011).

Although many studies evaluated moisture and compressive properties of knitted fabrics, a gap in knowledge was found regarding variability of compression between dry and wet conditions, which is relevant for sports bras that are worn in sweaty conditions (Maleki et al., 2011; Liu & Hu 2011; Öner & Okur, 2013; Tiwari et al., 2013). Therefore, the purpose of this small experimental study was to investigate how compression of seamless knitted fabrics changes between dry and wet conditions.

Materials and methods. The experimental samples consisted of 6 different fabrics knitted on a 15" diameter Santoni Top-2 circular knitting machine. Three different yarns were combined to knit a jacquard pattern that alternated 1" circular wool patches within a polyester yarn background, all using plain jersey stitches. The reason for choosing wool and polyester was to maximize fabric deformation when activated by moisture, due to opposite moisture management properties of the two fibers (Sarkar et al., 2010; Gorea et al., 2020). The first yarn was undyed, 19.5 Nm, 90% wool 10% Nylon, 60/1 in both S and Z twist, from Sudwolle, Germany, currently in use by several commercial sports bra brands. The base polyester yarn was Repreve 1/70/68 and the yarn for plating was a 20D spandex air covered with 1/40/13 polyester, both from Unifi, USA. The knitting parameters and physical measurements of the fabrics are shown in Table 1. The seamless knitted tubes were air-dried for 48 hours in standard conditions (20 °C, 60% RH), then laundered in cold water (60 °C) for 60 minutes in a revolving drum washing machine (GE) and tumble dried at low temperature (70 °C) for 90 minutes, in order to relax the knitting, but not alter the wool yarn texture (Choi & Ashdown, 2000).

A medical grade Kikuhime (TT Meditrade, 2019) device with a special air filled pressure probe (3 cm in diameter and about 3mm thickness) connected to a digital display device was used to measure the pressure between knitted tubes and the body of an Alvaform swimwear mannequin size 36B, at three different points equally placed 1" away around the apex of each breast (Brophy-Williams et al., 2014). The measurements were made in standard atmospheric conditions (20 °C, 65 % RH), with each knitted tube sample placed at the same bust level and trimmed to measure 13" flat width in relaxed state. For the

pressure measurements in the wet condition, an experimental set-up was created to replicate sports bra sweating patterns (Smith & Havenith, 2012). Since most of the sweat accumulates between the breasts, a triangular cutout template was created to match the spacing between the breasts and placed at center front on the knitted tubes on the mannequin. A spray bottle was used to apply 2.5grams of water in the center of the template, allowing the moisture only between the breast area. All 6 pressure readings for each sample were averaged for each sample in dry condition as well as in wet condition, and one- way ANOVA repeated measures analysis was conducted.

Table 1. Knitting parameters for all fabric samples.

SWATCH #	Stitches/ inch	Courses/ inch	Density*	Weight (gr/cm2)	Stitch length **	Plating yarn tension (gr)	Body yarn tension (gr)	Plating yarn combinations ***
Sample 01	86	74	6372	2.21	80	2.5	4	plated all throughout with spdx yarn
Sample 02	114	80	9151	2.98	80	2.5	4	plated with spdx yarn, but in the wool areas float the spdx yarn
Sample 04	87	83	7226	2.32	80	2.5	4	plated with the spdx yarn, but added 1 x 1 jacquard pattern in the wool areas with the spdx floated
Sample 05	96	85	8170	2.45	70	3.5	5	plated all throughout with spdx yarn
Sample 06	125	87	10872	3.26	70	3.5	5	plated with spdx yarn, but in the wool areas float the spdx yarn
Sample 07	94	85	8027	2.41	70	3.5	5	plated with the spdx yarn, but added 1 x 1 jacquard pattern in the wool areas with the spdx floated

Notes: * Density calculated as stitches/inch x courses/inch

** Stitch length is unitless, on a scale from 0 to 250.

*** Sample 03 was removed due to separating wool floats when stretched out.

Results and significance. The mean pressure decreased from 8.47 mmHg ($SD=1.82$) in dry condition to 6.94 mmHg ($SD=1.45$) in wet condition, and the mean difference between the dry and wet conditions was 1.53mmHg, significant at 0.05 level. Moreover, the main effect of density on pressure was found significant at the same 0.05 level. Figure 1 plots the results, showing sample 06 having the largest difference in pressure between the two moisture conditions (1.33 mmHg), while Sample 02 displayed the least effect (0.89 mmHg). The main difference between these 2 knitted fabrics was that Sample 06 had tighter stitch length and higher yarn tensions, therefore the results suggest that, for this particular stitch and yarn combination, a more tensioned construction will result in a greater variability of compression between dry and wet conditions.

Even if this experimental study had many limitations, these results are important for the future design of sports bras, when knitted stitch patterns and yarns are considered for engineered breast support. However, the variability of compression should be further studied and effects of other properties, such as elongation and air permeability, shall be investigated. The use of Kikuhime pressure sensors to establish precise ranges of compression levels for medical grade apparel is common, but compression in sports bras is categorized in a less scientific manner. Further larger studies on the feasibility of such a method shall be conducted.

Figure 1. Graphic representation of average pressures for each sample in each condition (dry and wet).

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