THERMAL COMFORT PROPERTIES OF KNIT-PLATED FABRIC MADE OF BALLISTIC NYLON WITH WOOL

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Abstract: *Recently knitted fabrics structure was developed for protective garments. The new fabric made of ballistic nylon plated with wool called knit-plated was designed and evaluated for thermal and water-vapour resistance. Also, the moisture management properties were investigated to measure the enhancement of wool to the fabric. The surface properties of the fabric, including coefficient of friction and surface roughness, were measured. The results indicates that the ballistic nylon-wool achieved good thermal comfort as well as the wool provide an average accumulative one way water transport. Furthermore, the results reveal that the fabric has smooth surface in the next-to-skin side due to plated wool.*

Keywords: *ballistic nylon, thermal comfort, knit plated, moisture management, surface roughness.*

1 INTRODUCTION

Knitted fabric structures have been used in deferent applications that include protective apparel such as firefighter clothes and soft body armour [1]. Most ballistic body armours used today consist of multiple layers of fabric and are made of expensive high-performance fibres such as Kevlar, Zylon, Twaron or Spectra [1, 2]. Several knitted structures, including single jersey, plush, interlock and 1×1 rib, have been investigated to understand their stab and cut resistant performance. Flambard [2] developed a plush and single jersey knitted fabric using an 18 gauge circular knitting machine. The fabrics were produced using spun yarns of Zylon and Kevlar®29 and weight 2640 g/m^2. Alpyildiz [1] proposed a new style of knitted structure fabric called “double-face” and “double-face-Inlay” for stab and cut resistance by using a flat knit machine. The yarns used were similar to those used by Flambard [2].

However, the thermal comfort properties of the knitted ballistic fabric were not examined in most of this literature. Traditional protective garments used are heavy, bulky, inflexible, and uncomfortable to wear, especially in hot-humid climates [3]. On the other hand, Mahbub [4] has developed a weft-knit plated Kevlar-wool for seamless soft body armour panel for female police officers. The panel consist of five layers, the first layer was made of Kevlar-wool plated and the rest were made of 100% Kevlar plated, the weight were 555 g/m^2 and 520 g/m^2 respectively. In addition, the body armour panel and its fabrics were tested and evaluated for thermos-physiological comfort. The results revel that both fabrics provided a moderate comfort as a multi-layer panel and single fabric [5].

In this study, the Knit-Plated structure made of ballistic nylon-wool fabric was manufactured based on the Mahbub [4] "weft-knit plated" Kevlar-wool fabric, and wool has been incorporated in the fabric to enhance the thermal comfort performance. In addition, ballistic nylon was used to reduce the fabric cost in compares with Kevlar price. The physical properties of the designed knitted fabric was tested and evaluated for thermal and water-vapour resistance. The Sweating Guarded Hot-Plate (SGHP) was used to simulate the heat and processes that occur between the skin and the fabric. Also, the moisture management performance was determined by using the Moisture-Management Tester (MMT), which was used to measure liquid moisture transport behaviour of the fabric including the liquid absorbency, liquid spreading and transport of water through the fabric. In addition, the surface friction was investigated to determine the roughness of the fabric.

1.1 Research objectives

The research aim to evaluate the thermal comfort properties of the developed ballistic nylon wool fabric to determine the enhancement of wool plated to the fabric structure. The objectives are:

1- to measure the thermal and water resistance in order to regulate fabric comfort.

2- to evaluate fabric moisture management properties in order to provide good moisture transfer properties.

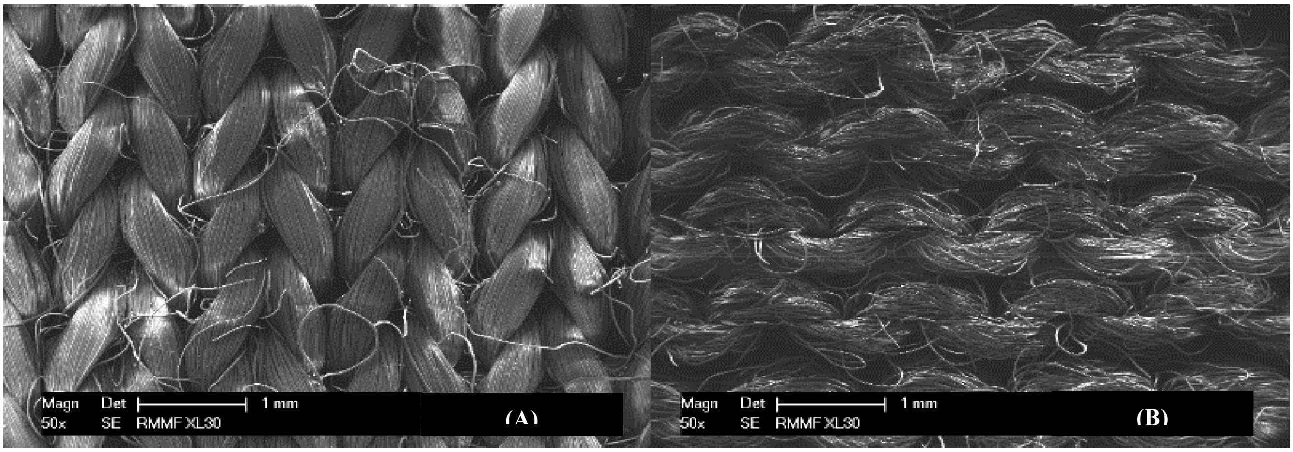

Figure 1 Front face made of ballistic nylon (A) and back face made of wool (B)

2 MATERIAL DESIGN

2.1 Yarn

The yarns used in this study were 93 tex continuous filament of ballistic nylon and 41 tex wool, spun two-fold yarn.

2.2 Ballistic nylon-wool (BNW) fabric production

The BNW fabric was produced using a flat knitting machine Shima Seiki SES-S.WG® and its CAD program. The knit-plated fabric made of ballistic nylon and wool yarns was produced at 18 gauges with 30 knitted fabric quality (tightness). The fabric structure was designed as a single jersey weft-knitted and is illustrates in Figure 1(A, B). The ballistic nylon has been knitted on the front face Figure 1(A) and Figure 1(B) shows the wool yarn plated on the back of the fabric.

3 METHODS AND METHODOLGY

The BNW fabric's physical properties, includes fabric thickness, mass per unit area and dimensional change, were tested. The following standards were used: AS 2001.2.15-1989 for fabric thickness, AS 2001.2.13-1987 for mass per unit area and AS 2001.5.4-1987 for dimensional change. The thermal and water-vapour resistance were measured according to ISO 11092:1993, while moisture management according to AATCC TM 195-2009. In addition, the Automatic Surface Tester (KES-FB4-AUTO-A) was used to measure the surface friction and roughness. The fabric specimens were conditioned for 24 hours under standard conditions of 65±3% relative humidity (RH) and temperature of 20±2°C, according to the Australian Standard AS 2001.1-1995.

3.1 Dimensional change test (D_C)

Three specimens from BNW fabric were marked (200×200 mm) and measured, avoiding the fabric edge by 25 mm. Three pairs of marks parallel to the course and wale directions were drawn. The distance between each pair was measured and recorded. The washing procedure used was (3A) gentle heating and rinsing in 20±3°C for a horizontal machine with household detergent (Surf brand). The samples were dried by flattening the fabric on a table until completely dried. Measurement after washing was recorded. The percentage change was calculated using equation (1):

$$D_C = (D_a - D_o)/D_o \times 100 \quad (1)$$

where: D_c = percentage change in dimension, D_a = dimension after washing and D_o = initial dimension.

3.2 The sweating guarded hot-plate (SGHP)

The designed fabric was tested for thermal and water-vapour resistance before and after washing to measure the difference that could occur. The test specimens were cut as squares of 300×300 mm. Three specimens were tested and the arithmetic mean of three individual reading for each sample was recorded and the standard deviation (*SD*) was calculated. The thermal resistance test measures the energy required to maintain a constant temperature of 35°C on the surface of the measuring plate [6]. Both thermal measurement unit temperature and the thermal guard temperature were set to 35.0°C. The air temperature was 20.0°C and the relative humidity was 65%. The air speed was 1 m/sec. The thermal resistance for the fabric was calculated by measuring the heat temperature between the plate surface and the surrounding ambient air every 15 minute [7].

The water-vapour test measured the power required to keep a constant vapour pressure between the top and the bottom surface of the fabric [8]. The test recorded the average power required to keep the measuring unit at its selected temperature based on 15 minute integration. The value of the arithmetic mean of three reading results from each fabric was calculated. The test atmosphere was 35.0°C and 40% relative humidity for the water-vapour test measurement unit. The thermal guard temperature was set to 35.0°C and the air speed was 1 m/sec. The water-vapour resistance results were calculated by the vapour pressure difference between the saturated plate surface and the ambient air according to the Standard [7].

3.3 Moisture-management tester (MMT)

The MMT instrument was used to test the liquid solution transfer and distribution behaviour. The test started by placing an 80×80 mm test specimen between two horizontal electrical sensor rings. A saline solution (9 g sodium chloride per liter) was dripped freely onto the top surface at the centre of the fabric. As the solution moved, the moisture behaviour of the test specimen was measured and recorded. The MMT parameters measured were:

- Wetting time - the time in which the top and bottom surfaces of the fabric just started to get wet respectively after the test commenced. The results can be explained as following: **1)** ≥120 no wetting; **2)** 20-119 slow; **3)** 5-19 medium; **4)** 3-5 fast; **5)** <3 very fast.
- Absorption rate - the average moisture absorption ability of the fabric's top and bottom surfaces during the rise of water content, respectively. The results can be explained as following: **1)** 0-10 very slow; **2)** 10-30 slow; **3)** 30-50 medium; **4)** 50-100 fast; **5)** >100 very fast.
- Maximum wetted radius - defined as the maximum wetted ring radius at the top and bottom surfaces, respectively. The results can be explained as following: **1)** 0-7 no wetting; **2)** 7-12 small; **3)** 12-17 medium; **4)** 17-20 fast; **5)** >22 very fast.
- Spreading speed - the accumulative spreading speed from the centre of the fabric sample to the maximum wetted radius. The results can be explained as following: **1)** 0-1 very slow; **2)** 1-2 slow; **3)** 2-3 medium; **4)** 3-4 fast; **5)** >4 very fast.
- The accumulative one-way transport capability (OWTC) - which measure the water content between the two surfaces. The higher results indicate that the quicker and easier for water to transfer to the atmosphere from the skin. The results can be explained as following: **1)** <-50 very poor; **2)** -50-100 poor; **3)** 100-200 good; **4)** 200-400 very good; **5)** >400 excellent.
- The overall moisture management capability (OMMC) - indicates the capability of the fabric to manage the transport of the water. In other words, the higher result means better moisture management. The results can be explained as following: **1)** 0-0.2 very poor; **2)** 0.2-0.4 poor; **3)** 0.4-0.6 good; **4)** 0.6-0.8 very good; **5)** >0.8 excellent.

3.4 Automatic surface tester

The coefficient of friction (MIU) and the surface roughness (SMD) was measured. The test was on the wool face of the BNW, which represent the next-to-skin side, of the fabric. Three fabric samples were cut to 200×200 mm and then placed under the test sensor, which measures the friction at three different positions on each specimen from the next-to-skin side. The wales and courses directions were measured and the arithmetic mean was recorded. The range for MIU is from 0 to 1, where the value close to 1 indicates increasing friction and decreasing smoothness. The range for SMD is range among 0 to 20, the value of 20 can be considered as the maximum surface roughness (irregularity) [9].

4 RESULTS AND DISCUSSION

The BNW fabric physical properties results are shown in Table 1.

Table 1 Fabric physical properties

Knit-plated Fabric (BNW)		
Thickness [mm]	**Mass per unit area [g/m²]**	**Dimensional change [%]**
1.2	530	wales -1 courses -2.5

It can be seen that the BNW fabric has reasonable thickness however the fabric mass is heavy with 530 g/m^2. Furthermore, the BNW dimension has changed after washing due to the nature of wool fibre. The wales direction shrunk about (-1%), while the courses lost more than with (-2.5%) of it dimension due to the plated wool in the back as shown in Figure 1.

4.1 Thermal and water-vapour resistance

The thermal resistance results before and after washing are shown in Figure 2.

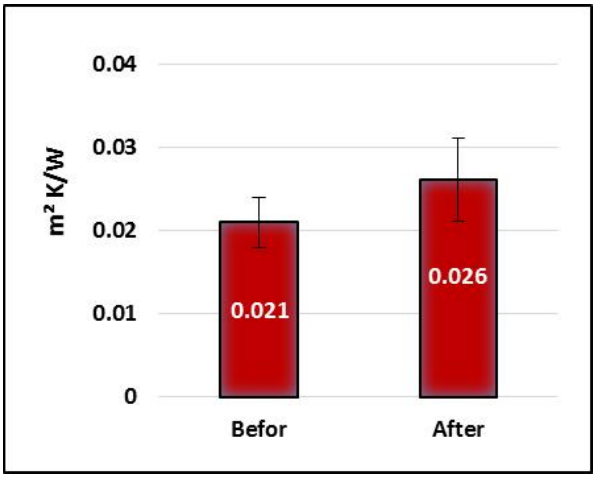

Figure 2 Thermal resistance results

The results reveal minor increase in thermal insulation after fabric been washed, which could be due to the fuzz of wool fiber that appear after washing. In addition, the BNW fabric is heavy and has achieved almost the high rate of thermal resistance value of 0.026±0.01 m².K/W. Data indicates that the developed fabric can transfer heat away, hence can be considered as comfortable in moderate activity. According to the Standard, the thermal resistance for heavy-weight fabrics should be between 0.02 and 0.025 m².K/W.

Water-vapour results are shown in Figure 3. The results indicate slight increase about 0.17 m².Pa/W. Therefore, the fabric can be considered as a comfortable and breathable fabric.

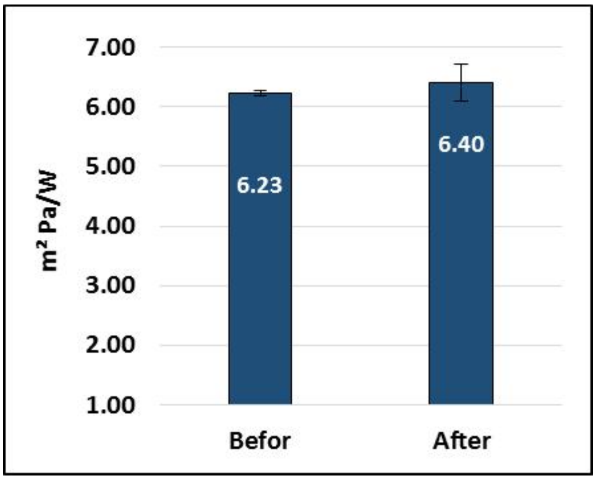

Figure 3 Water-vapour resistance

According to Horrocks [8], if a fabric achieves a value less than 20 m².Pa/W, it can be considered as breathable and comfortable at a moderate activity rate. The BNW fabric after wash was 6.40 m².Pa/W, which is less than the standard.

4.2 Moisture-management

For the MMT tests, the ballistic nylon face was on the bottom surface (UB) of the machine, which is the outer-to-skin side of the fabric. The plated wool was located on the next-to-skin side, which represent the top surface (UT) of the machine. The moisture measurement properties for the BNW are summarized in Table 2.

Table 2 Fabric MMT results

	UT	UB
Wetting time [s]	15.2	30
Absorption rate [%/s]	37.3	25.5
Wet-out radius [mm]	15	19
Spreading speed [mm/s]	1.3	2.5
OWTC [%]	145.8	
OMMC	0.4	

The results show that the wetting time between the two surfaces is varied. The low wetting time and high absorption rate of the wool surface suggest that the wool surface can absorb water faster than the ballistic nylon surface. Hence the wool face is next-to-skin for better moisture management. In addition, Figure 4 shows the water content versus times and confirms that the wet-out radius for UT was lower than UB, which means UT has a moderate ability to transfer the absorbed water to the outer surface.

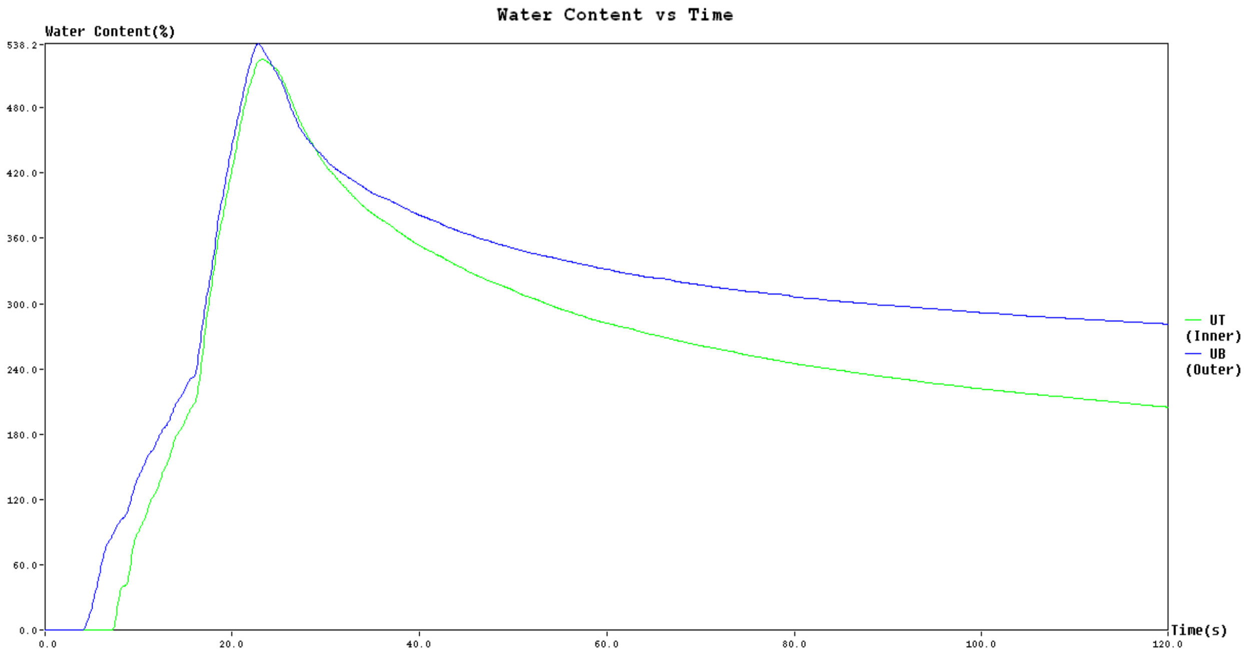

Figure 4 Water content versus times

Figure 5 shows the wet-out radius difference between the two surfaces.

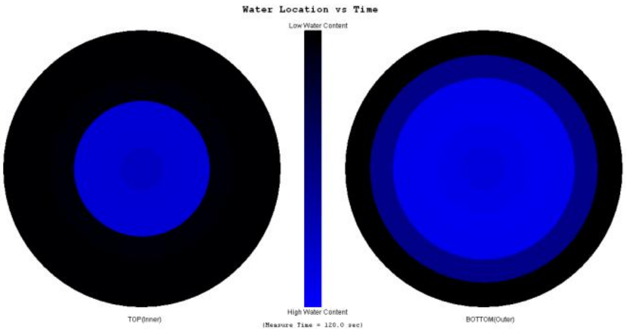

Figure 5 Fabric moisture transport

The result reveals that the BNW fabric has a relatively large spreading rate (2.5 mm/s) and large wet-out radius (19 mm) on the UB, indicating that liquid can spread quickly, transfer easily and dry quickly on the outer surface of the fabric. The fabric OWTC was 145.8% and the OMMC was 0.4 hence, the grade was good. Figure 6 illustrates the finger print of the BNW fabric, which is the moisture management property for all the parameters. This is indicating that the BNW knit-plated fabric has an average water penetration between both surfaces.

4.3 Surface friction (MIU) and roughness (SMD)

The fabric coefficient of friction and the surface roughness are shown in Table 3 for both wales and courses directions.

Table 3 Surface properties

coefficient of friction (MIU)		surface roughness (SMD)	
wales	course	wales	course
0.33±0.099	0.19±0.001	17.25±0.94	4.37±0.57

The table reveals the significant differences between the wales and course directions with 0.33 and 0.19 MIU, respectively. This due to the wool plated in the next-to-skin side as the course direction would be smoother than the wale direction, which can be confirmed in Figure 1(B) for the back face structure. According to machine manual [9] the range for MIU is from 0 to 1, where a value close to 1 indicates increasing friction and decreasing smoothness. In addition, the BNW has a low coefficient of friction in both direction with (<0.05) and can be considered as a smooth fabric when it be worn in the next-to-skin.

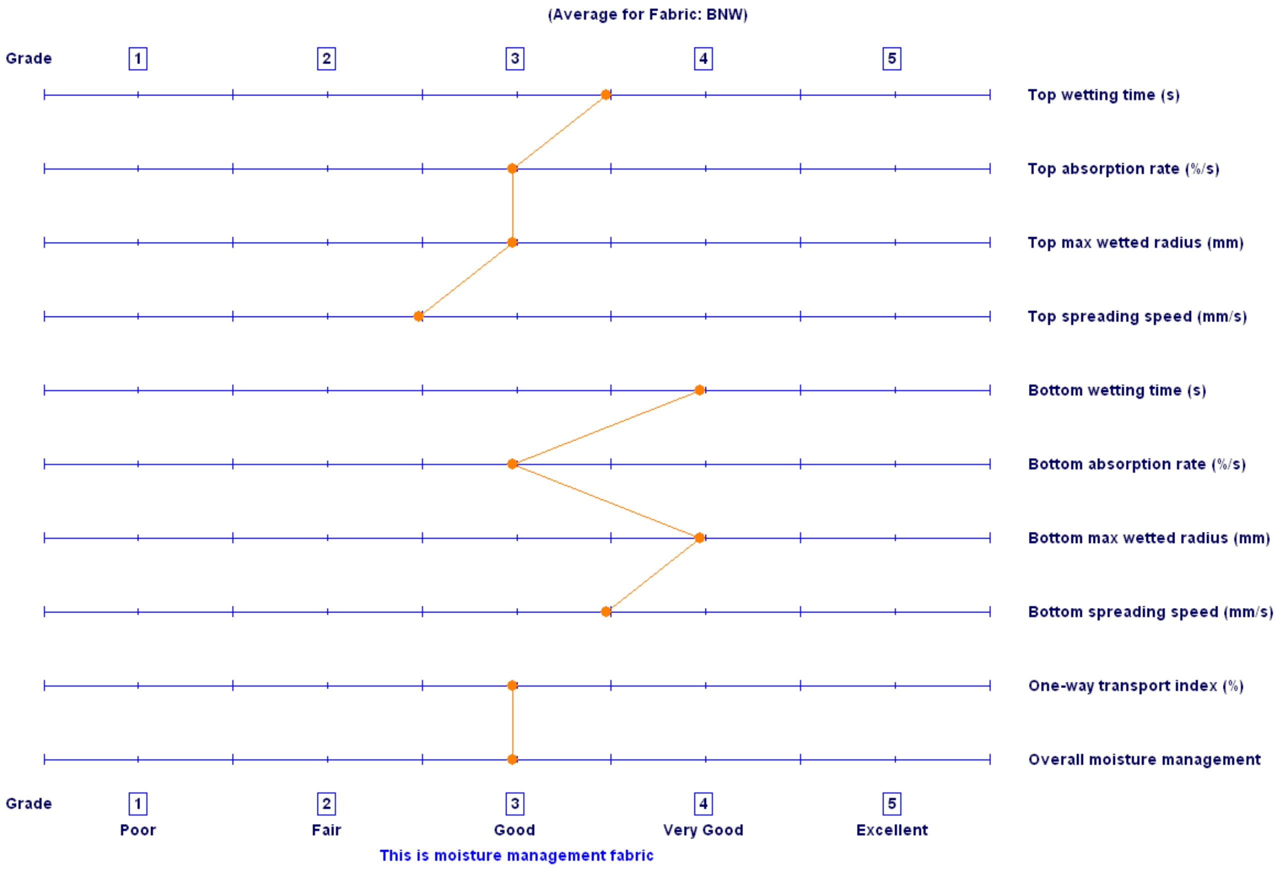

Figure 6 Fabric finger print of MMT properties

The fabric surface roughness is shown in Figure 7. It can be seen that the wale direction roughness is higher than the course with 17.25 SMD. On the other hand, the roughness is remarkable in the course direction with 4.37 SMD, indicating the less regularity that the wale.

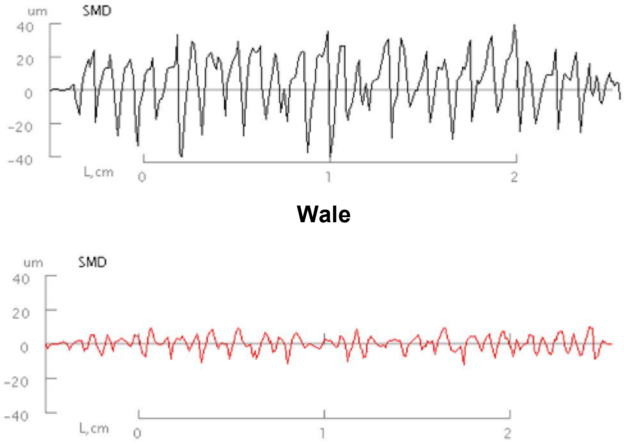

Figure 7 Fabric surface roughness (irregularity)

According to the machine manual [9] for SMD the range is among 0 to 20, the value of 20 can be considered as the maximum surface roughness (irregularity). In spite of the low SMD in the course direction, the wale illustrates the high surface roughness close to the 20 SMD. This is due to the plated structure of the back face of the BNW fabric which cases the irregularity. From the results it can be reveal that the BNW fabric has low coefficient of friction and high roughness in the next-to-skin side.

5 CONCLUSION

A new weft knit-plated fabric made from ballistic nylon and wool using a flat knitted machine was developed. The thermal and water-vapour resistance were evaluated for comfort. Also, the moisture management performance and the surface properties were measured. The results reveal that the new fabric has good thermal and water-vapour resistance and can be considered as comfortable in moderate activity rate. Furthermore, plating wool into the fabric produced good moisture absorbency and transport properties. The fabric shows high irregularity in surface roughness (SMD) and low value of coefficient of friction (MIU), the fabric can be worn next-to-skin.

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