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Knitted Coil for Inductive Plethysmography †

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Abstract: Knitting a thin insulated metal wire simultaneously with elastic yarn in the round creates a coil with a self-inductance close to a wound coil. This knit is flexible and can be stretched, allowing the diameter of the coil to change, resulting in a change of its self-inductance. It is found that rib stitch gives the highest inductance but stocking stitch gives the highest variation of self-inductance with changing diameter. The feasibility of using the knitted coil for inductive plethysmography is demonstrated by simulated breathing in a baby jumper with knitted coils.

Keywords: knitted coil; inductive plethysmography; e-textile

1. Introduction

Inductive plethysmography, first reported by Konno et al. in 1967 [1], measures the variation of the changes of the diameter of the thorax and/or abdomen during breathing via changes in the inductance value of a coil. Traditionally, the coil is made from an insulated metal wire integrated in an elastic band. The metal wire is attached to the band in an undulating way such that it allows stretch [2]. Sending a small AC current through the wire allows measurement of the self-inductance of the wire that changes as a function of diameter of the band. This implementation can measure the respiration signal and air volume. It is one of the different non-invasive approaches to measure respiration [3] and is considered a good alternative for long-term monitoring. In the current implementations, the coils can change in position and shape creating undesirable inductance changes. A possible solution is to integrate the bands in a tight-fitting garment to improve the synchronous measurement of movement of thorax and abdomen. The Respibelt [4] is an example of a knitted coil that is made from stainless steel yarn knitted in a Lycra-containing belt to allow stretch. Respibelt measures changes in both inductance and resistance. Knitted garments are inherently elastic and able to stretch due to the horseshoe character of the interlinked stitches making them suitable for this application. In this work, we investigate an alternative way to implement a coil in a knit. Yarn and thin insulated metal wire are knitted simultaneously in the round. Knitting in the round ensures continuity of the current flow and current direction through the different kitted rows. This implementation is equivalent to a wound coil with the number of knitted rows analogous to the number of coil windings. The self-inductance of the knitted coil follows that of a wound coil closely and the knit retains full elasticity as long as the chosen metal wire is thin [5]. Although, the implementation does not compromise on the wearability of the garment, the compromise is an increased length of the metal wire and thus results in higher resistances. Therefore, the number of knitted rows (turns) with wire is restricted to $N = 5$. The insulated Cu wire used is ~150 µm thick. Using thicker wire gives lower resistance but less wear comfort. This manuscript gives an overview of the result of investigations of the influence of different knit parameters on the variation of the self-inductance under stretch. The stretch is achieved by fitting the garment onto cardboard cylinders with different diameters or onto balloons, the circumference of which can be dynamically changed by pressing the balloon.

2. Materials and Methods

In this section, we investigate the influence of the stitch pattern, the chosen yarn, and the number of stitches for the same stretched diameter. The chosen initial diameter for this investigation is that of a cuff—approximately 66 mm.

The basic stitches are called knit (V-shape) and purl (bar). The three basic patterns investigated in this work are: garter, stockinette, and 1/1 rib (Figure 1a). The main difference between these is how the stitches interlink in the course and wale direction (Figure 1b). The horizontal (course) parts of the stitch form the "traditional" winding of the coils. They are similar for all stitch patterns only different in how the bars are at the front or back of the garment. The main difference is how the vertical (wale) parts interlink. In Figure 1c the knit, made with thick yarn, is stretched, highlighting the differences between the stitch crossover points. The currents through the vertical parts of the neighboring stitches flow in opposite direction, cancelling their contribution to the inductance. However, those points where the yarns sit most closely together have a large impact on the inductance as shown by Equation (1) for the self-inductance of an arbitrarily shaped coil [6]:

$$L \approx \frac{\mu_0}{4\pi}\left(\oint\!\!\oint \frac{dx_1 \cdot dx_2}{|x_1 - x_2|}\right)_{|s_1 - s_2| > a/2} + \cdots, \tag{1}$$

with a, the wire diameter; l, the length of the wire; and s, the length along the wire axis. The denominator $|\boldsymbol{x}_1 - \boldsymbol{x}_2|$ highlights the importance of those areas where x_1 is close to x_2.

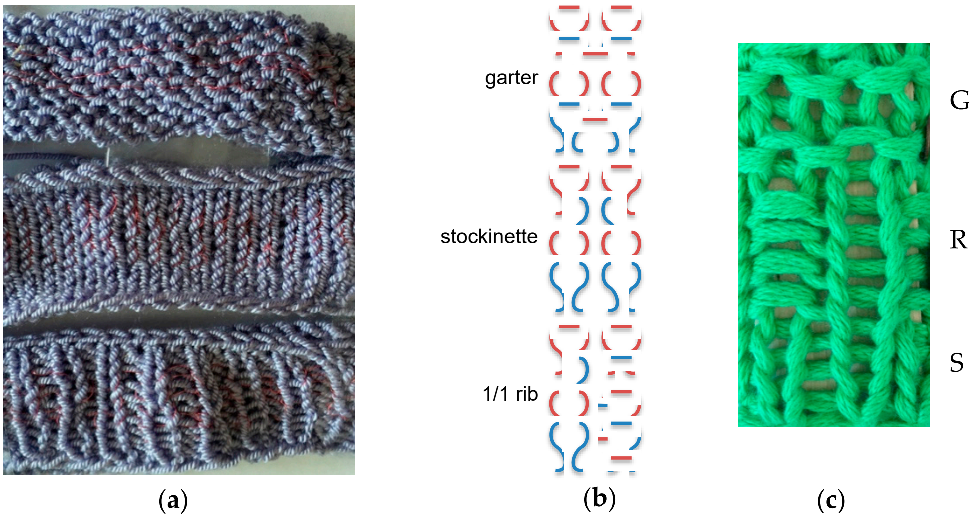


Figure 1. (**a**) Picture of the knit patterns. Elastic viscose yarn, Cu insulated wire (red), needles 3.5 mm. (**b**) Sketches of the patterns showing the difference in stitch overlap. (**c**) Knits in thick yarn to show the difference in stitch overlap under stretch between G: garter, R: 1/1 rib, and S: stockinette.

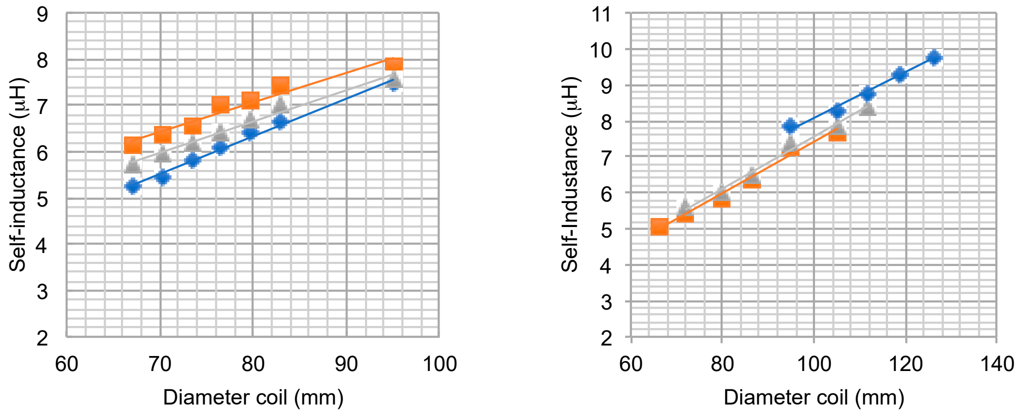
For the measurements, the cuff-sized knits are held on cardboard cylinders and stretch is applied by using cylinders with increasing diameter. The self-inductance is measured using a Wayne Kerr 6500B in a frequency range of 1–100 kHz and the values are reported at f = 53 kHz. The AC bias is 50 mV. No DC bias is applied.

For the simulated breathing, the knits are held on an inflated balloon and the circumference is measured with a tape measure. This reduces the accuracy in diameter as the balloon is not cylindrical and the tape measure is only accurate to 1 mm. The implementation however gives an easy way to simulate breathing by dynamically changing the diameter of the balloon.

3. Results

In Figure 2, we show the variation of the self-inductance of a cuff when increasing the diameter via stretch. Figure 2a gives the influence of the chosen pattern, while Figure 2b gives the influence of the number of stitches in the knit for the same stretched diameters. All results are for elastic viscose yarn, knitted with needles of 3.5 mm and $N = 5$.

Figure 2a shows that rib stitch gives the highest inductance value but stockinette gives the highest variation of the self-inductance with diameter upon stretch. As explained in Section 2, the character of the interlinked stitches determines these differences. Increasing the number of stitches for the same stretched diameter gives only small variations in response (Figure 2b). Thus, the results for the response of the cuff can be extrapolated to that for a knit with larger initial diameter. The knits used for the blue diamonds in Figure 2a and the orange squares in Figure 2b are different knits with the same yarn and Cu wire and their close results demonstrates the reproducibility of the knit and its response to stretch.



(**a**) (**b**)

Figure 2. Inductance as a function of diameter upon stretch. (**a**) Influence of the pattern. Number of stitches N_S per row is 54 for all patterns. Garter triangles; stockinette diamonds; and rib squares; (**b**) Influence of N_S for stockinette. Squares: 54, triangles: 60, and diamonds: 84.

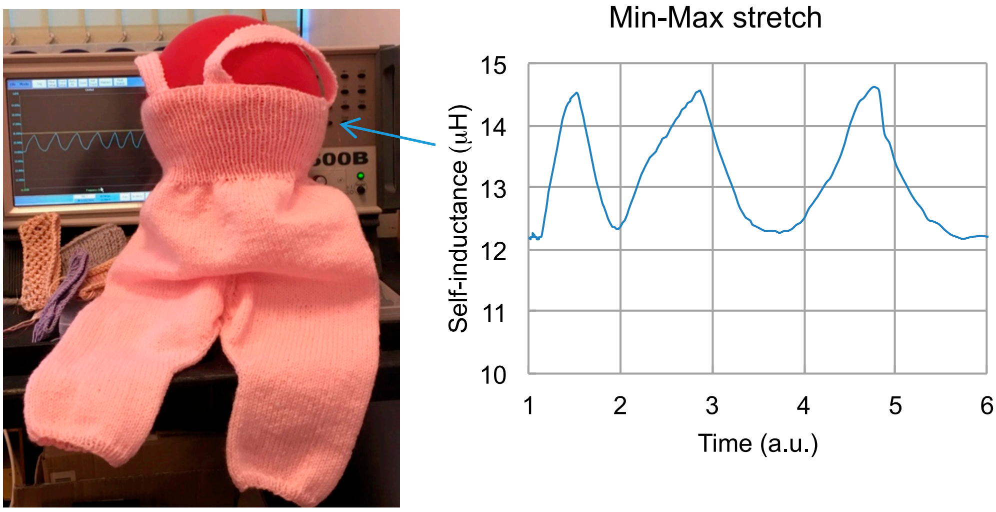
Table 1 gives the values for the variation of the self-inductance as a function of diameter $\Delta L/\Delta D$ upon stretch for different yarn choices and different stitch patterns. Measurements for larger diameters that suit a baby romper ($N_S = 100$, elastic viscose yarn, needles 3.5 mm, $N = 5$) are given in the last row. The results demonstrate that the response of the knitted coil as a function of stretch is mainly determined by the diameter and the chosen pattern. Viscose yarn and stockinette give the highest sensitivity. Repeating the stretch–relax measurement multiple times gives $\Delta L/\Delta D$ between 0.09 and 0.084 µH/mm, showing reasonable repeatability.

Table 1. $\Delta L/\Delta D$ upon stretch for different yarn choices and different stitch patterns.

$\Delta L/\Delta D$ (µH/mm)	Rib	Garter	Stockinette
Viscose 3.5 mm	0.064	0.068	0.081
Cotton 3 mm	0.059		0.062
Cotton 7.5 mm	0.053		0.053
Viscose 3.5 mm [1]	0.072		0.084

[1] for 100 stitches (size of a baby romper body).

A baby romper was knitted in stockinette in non-elastic yarn using 3 mm needles, see Figure 3a. Two coils were integrated in the body of the romper suit, one at the top and one at the bottom. A balloon was used to simulate breathing by pressing on the balloon, changing its circumference between 44 and 53 cm. This 9 cm variation is much larger than the abdomen circumference variations of a normal infant during breathing which is ~3 cm in sleeping babies [7]. A stretch of 3 cm in circumference would translate into an inductance change of ~0.6 μH in the knitted coil. Figure 3b shows the variation of the self-inductance as a function of time during simulated breathing for a balloon circumference variation between 44 and 53 cm.



(a) (b)

Figure 3. (**a**) Knitted baby romper with knitted coils in rib. (**b**) Self-inductance for simulated breathing, 44 cm < circumference < 53 cm. The result is given for the body in stockinette.

4. Conclusions

Knitting a thin insulated metal wire simultaneously with yarn has the characteristics of a wound coil if the knit is in the round. It was found that although rib stitch gives the highest self-inductance, the sensitivity of stockinette expressed in terms of change of the self-inductance with diameter under stretch is highest. The best results were obtained for stockinette in elastic viscose yarn, giving $\Delta L/\Delta D \approx 0.09$ μH/mm. This sensitivity is independent of the initial diameter of the garment showing that the variation in self-inductance is mainly determined by the variation in diameter. The influence of the stitch pattern is associated to the crossover points between the stitches in the wale direction that is different for the different patterns. Simulated breathing was demonstrated with a baby romper with integrated coils.

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Conflicts of Interest: The authors declare no conflict of interest.

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