Knitted coils as breathing sensors

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Highlights

- Knitted coils in which a thin insulated Cu wire is knitted simultaneously with yarn gives supple, wearable garments for non-invasive inductive measurements of diameter changes.
- The variation of the self-inductance with diameter of knitted coils is linear.
- The sensitivity of a knitted wearable coil with thin insulated Cu wire and elastic viscose is $\Delta L/\Delta D$ = 0.84 μH/cm (L: self-inductance and D: diameter).
- Knitted coils in 1/1 rib stitch have the highest self-inductance for a given, supported, non-stretched diameter, independent of yarn type.

Keywords
Inductive plethysmography
Knitted coil
Wearable sensor

Abstract
A new implementation of a wearable respiratory inductive plethysmography garment is obtained by knitting a 250 μm thin insulted Cu wire simultaneously with yarn in the round. This was used to integrate a knitted coil in the body of a baby romper suit. During simulated breathing the diameter of knitted coil changes by stretching the knit circularly, causing a variation of the self-inductance of the coil. Coils with 5 rows of integrated metal wire with different stitch types and patterns were investigated to determine their influence on inductance, series resistance and sensitivity. We observed that knit styles that reduce the resistance of the coil, such as lace and jacquard also reduce the inductance and flexibility of the garment. Jacquard with three colours and one metal wire for each colour, gave the highest coil quality factor but also the poorest flexibility. We found that 1/1 rib stitch has the highest self-inductance for all yarn types. Its sensitivity of 0.5 – 0.6 μH/cm is similar to stockinette stitch except when elastic viscose yarn is used. Coils in stockinette stitch and elastic viscose yarn have the highest sensitivity of 0.84 μH/cm. No hysteresis in self-inductance was observed for circumference variations between 44 and 53 cm of the body of the baby romper in 1/1 rib stitch due to the elasticity of knitted garments.

1. Introduction

The ability to observe respiration is at the very core of healthcare diagnosis and monitoring, as many health conditions manifest themselves in characteristic breathing patterns; these include sleep apnoea [1], chest infections, tuberculosis [2], and stress [3]. The benchmark in respiration monitoring is esophageal manometry [4], whereby a probe is inserted through the nose into the stomach. The invasive nature of the method is prohibitive to its use in long term and out-of-hospital monitoring [5]. Hence, there is a significant drive towards finding alternative measurement techniques that are not invasive or obtrusive. Non-invasive techniques are in particular required for infants [6] and the elderly. Amongst many non-invasive approaches, inductive [7], resistive [8] and piezoelectric [9] plethysmography, are suitable for integration in garments for wearable monitoring systems. Piezoelectric plethysmography uses a piezoelectric material attached to one or two elastic bands that generate a voltage proportional to the pressure on the piezo-element. The system causes minimal discomfort since a piezo-element can be thin as its performance does not depend on thickness. Still, the bands, which are positioned around the abdomen and the thorax, are sensitive to core temperature changes, and in low-pressure situations deep exhalations are occasionally mistaken for neutral readings. Inductive plethysmography monitors respiration based on changes in the inductance of a metal coil during breathing. It is traditionally based on two elastic bands that comprise an integrated metal wire of sinusoidal shape. One band is positioned around the abdomen and the other around the thorax. Movement of abdomen and thorax during respiration lead to changes in the diameter of the coil and thus changes in inductance. Despite the high sensitivity, desirable for clinical studies with infants [10], using two bands tends to lead to measurement errors due to the shift in absolute and relative position of the bands. An alternative implementation of inductive plethysmography is the implementation presented in [8] where stainless steel yarn is used to knit the band. While inhaling, the inductance increases due to the increase in coil cross-section. At the same time, the resistance of the band will reduce because the stitch crossover points will press together, decreasing the resistance of the multiple contact points in the knit and thus the overall resistance of the band. The inductance variation as a function of elongation of the band is reported to be 0.05 μH/cm, and the resistor gauge factor is -0.53. In [11] we investigated the inductance of knitted coils where a thin insulated metal wire is knitted together with conventional yarn (see Fig. 1a). Like [8], this offers excellent wearability and an inductance that closely follows a traditionally wound helical coil. The difference with [8] is that the resistance does not change and that the knit is automatically insulated.

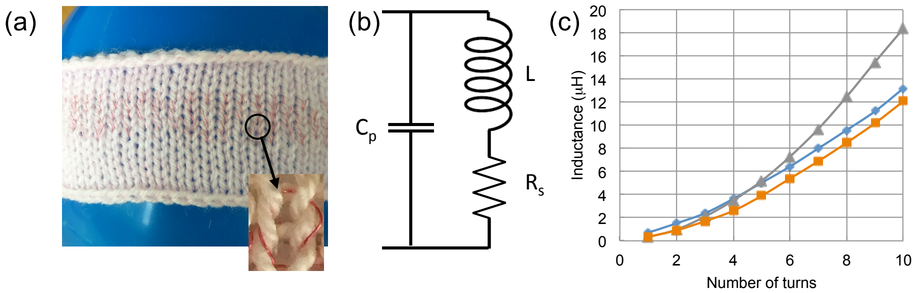

Fig. 1. a) Picture of a circular knitted coil, using 3 mm needles, 250 μm insulated Cu wire (red colour) and cotton yarn (white). The inset shows the thin metal wire in 1 stitch. b) Equivalent circuit of a helical coil. L: self-inductance, R_s: series resistance, C_p: parallel capacitance. c) Self-inductance as a function of number of turns [11]. Wound coil (triangles), inlaid coil (squares) and knitted coils (diamonds). The accuracy of the measurement is better than ±0.05%.

In Fig. 1c the variation of the self-inductance as a function of number of turns, *N* in three coil implementations is given. Triangles give the self-inductance of a closely wound coil with the same metal as that used in the knit. The diamonds are for the knitted coils in which the metal wire is introduced in all stitches of *N* = 1-10 rows. The square markers are for a coil embedded in the knit by sewing a long wire in *N* = 1-10 knitted rows (this approach loses flexibility). The way to ensure the knitted garment works as an inductor is to knit in the round such that the metal wire runs continuously from bottom to top in the knit, as explained in more detail in [11]. The self-inductance, *L* and parasitic-capacitance, C_p (see Fig. 1b) of such a knitted coil changes with diameter. This implementation opens the prospect of knitting two coils in the appropriate places of a snug-fitting garment, e.g. a body romper suit for infants, see Fig. 2b & c. The snug fit would both be comfortable and keep the coils in place while expanding/contracting with breathing. The integration of both coils in one garment will maintain better relative coil positioning, allowing for synchronous diameter changes of thorax and abdomen to be used to improve signal processing. At the low power levels (peak-to-peak ac voltage and current of 50 mV and <10 mA, respectively) and relatively low frequencies (53 kHz) used, the effect of the magnetic field on the human body is assumed to be negligible. Currently, no reliable evidence exists of the impact of these low frequency and low power level magnetic fields on health [12,13] and more research in this field is required, especially when long wear times are envisioned.

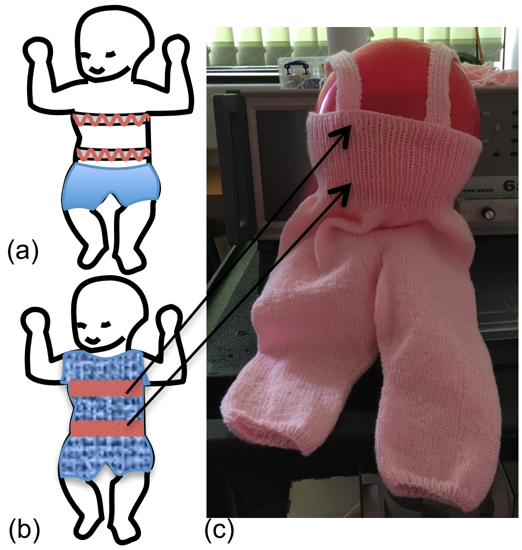

Figure 2: a) cartoon of two individual elastic respiration bands, b) cartoon of two coils integrated into the knit at the thorax and abdomen position. c) implementation of b) into a romper suit. The arrows indicate the position of the knitted coils. There are no seams in this implementation as the whole garment is knitted in the round.

This manuscript presents two aspects of research. The first is the study of the influence of the stitch type, yarn elasticity and yarn diameter on the self-inductance, series resistance and its sensitivity to diameter changes. The second is the variation of the self-inductance of the knitted romper in non-elastic and elastic yarn as a function of stitch type and a small variation in number of stitches. Simulated breathing results, using pressure on a balloon (see Fig. 2c) to dynamically change the diameter of the body of the romper suit, are also given.

2. Study of the impact of the knit style

In this section we study the influence of the knit type, yarn type and yarn diameter on the self-inductance under strain. The original knits are all designed for a non-stretched diameter of ~66 mm by adapting the number of stitches in a row in accordance with the gauge. The metal used in all

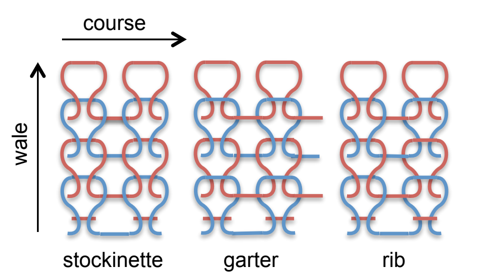

Figure 3: Schematic illustration of stockinette, garter and rib stitches. Note that the overlap of the adjacent stitches in the course direction (horizontal) and wale direction (vertical) is different in the different stitch styles.

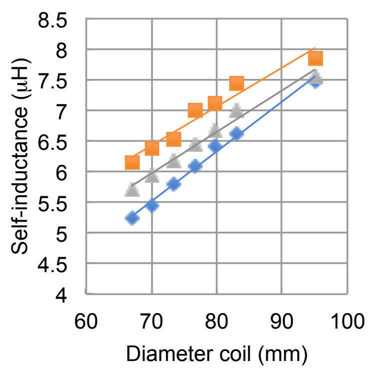

Figure 4: Self-inductance as a function of diameter for 3 stitch types. Squares: 1/1 rib, triangles: garter and diamonds: stockinette. The markers are the measurements and the lines are a linear fit through the measurements. *The accuracy of the measurement is* better than ±0.05%.

the knits is ~250 μm insulated Cu wire. The insulation is only a few micrometers thick, resulting in very thin and flexible wire. The number of rows, equivalent to the number of turns of the coil, is N = 5. The coil will therefore be longer for thicker yarn. All samples are hand-knitted in the round using 4 needles with a size appropriate for the yarn. The knits maintain their full elasticity and wearability.

Figure 5: Different stitches, yarn types and sizes. a1) lace using 2TOG, a2) lace using PSSO, b1) 2 colour jacquard in blocks of 2 stitches each with metal only in 1 yarn colour (not show b1: 2 colour jacquard in blocks of 2 stitches each with metal in both yarns), b2) 3 colour jacquard in blocks of 1 stitch each with metal in all three yarns, c1) stockinette, c2) 1/1 rib (a – c are all in size 3 mm cotton yarn), d1) stockinette, d2) 1/1 rib both in elastic viscose yarn size 3.5, e1) stockinette, e2) 1/1 rib both cotton yarn size 5, f1) stockinette, f2) 1/1 rib both cotton yarn size 7.5. Stitch abbreviations can be found in [14].*

Stockinette, garter and rib knits are simple standard knitting styles (Fig. 3). Stockinette is made by knitting only knit stitches (K) when knitting in the round and the garment presents all stitches as a K at the outside and a purl (P) at the inside of the fabric. Garter is obtained by knitting all odd rows in K and all even rows in P. 1/1 rib alternates K and P stitches. In the subsequent rows, K is knitted on K and P is knitted on P. Rib knit is often used for cuffs and borders because of it higher flexibility and good contraction tendency. The measurements are carried out using a Wayne Kerr 6500 B precision component analyser with the component fixture 1011 at a frequency of 53 kHz, a DC bias of 0 V and an ac bias voltage of 50 mV. At this low frequency the influence of the parasitic capacitance is negligible, confirmed by the constant value of the inductance L and series resistance R_s as a function of frequency (see supplementary information S1). The cuffs are supported by cardboard cylinders during measurements. 3 cyclinders are used with a diameter of 66 mm, 72 mm and 95 mm. Intermediate diameters are obtained by winding a layer of cardboard around a smaller cylinder. Fig. 4 gives the measurement of the self-inductance of 3 cuffs knitted in elastic viscose yarn using the three different stitch types: stockinette, garter and rib. The number of stitches is the same for the 3 cuffs. The markers are the measurements and the lines are linear fits to the measurements. The rib stitch gives a higher inductance than the garter stitch and the stockinette the lowest. However, the stockinette gives the highest variation of inductance as a function of diameter: $\Delta L/\Delta D$ = 0.081 μH/mm. $\Delta L/\Delta D$ = 0.064 μH/mm for the 1/1 rib and $\Delta L/\Delta D$ = 0.068 μH/mm for the garter stitch.

A further selection of cuffs was knitted with different yarns (cotton, elastic viscose), needle sizes (3, 3.5, 5. 7.5) and patterns (stockinette, garter, 1/1 rib, lace, jacquard), as shown in Fig. 5. Lace and jacquard knits minimise the series resistance of the coil by reducing the length of the knitted metal wire. All knits except those used for d1 and d2, in Fig. 5 are made in cotton. d1 and d2 are made with elastic viscose (the cuff in garter with the same yarn is not added to the picture). Cotton shows limited stretch along the length of the yarn: Δl ~103% of its original length, while the elastic viscose yarn stretches more: Δl ~166%. Yarn stretch is different from garment stretch where the stretch is due to the interlocking horseshoe shaped stitches rather than the yarn.
The results of the measurements for 3 cuff diameters are given in Table I.

Table I: Self-inductance and series resistance for the different cuffs given in Fig. 5 as a function diameter, D. L is the self-inductance, R_s the series resistance. The stitch type numbers correspond to those defined in Fig. 5.

***D* (mm)**	66		72		95	
Stitch	***L* (μH)**	***R***				

***D* (mm)**	66		72		95	
Stitch	***L* (μH)**	**R_s (Ω)**	***L* (μH)**	**R_s (Ω)**	***L* (μH)**	**R_s (Ω)**
D2	6.2	6.4	6.4	6.4	7.9	6.4
E2	5.9	6.3	6.1	6.3	7.3	6.4
F2	5.8	6.5	6	6.4	7.3	6.5
C2	5.6	6	5.9	6	7.3	6
A2	5.5	5.8	5.7	5.7	na	na
C1	5.5	6.1	5.6	6.1	7.2	6.2
E1	5.5	6.3	5.7	6.3	7.1	6.4
F1	5.4	6.6	5.6	6.5	6.9	6.5
D1	5.2	6.3	5.6	6.3	7.5	6.3
A1	5.1	5.1	5.4	5.1	na	na
C1*	5	3.2	5.2	3.2	6.8	3.2
C1**	4.9	2.2	5	2.2	6.6	2.2
B1	4.6	4.1	4.9	4.1	6.7	4.1
B1*	3.5	2.1	3.8	2.1	5.6	2.1
B2	3.1	1.1	3.4	1.1	na	na

The results in Table I indicate that the rib stitch gives higher inductance values than the stockinette stitch for all yarn types. Comparing the three stitch styles in Fig. 3, we notice that the top of the stitches along the courses in stockinette is always behind the legs of the stitches of the previous row. This gives and asymmetric side view profile, a smooth front and ridges at the back of the garment. For the garter stitch the position of the head of the stitch alternates between front and back for subsequent courses, giving a symmetric side view. For the rib, the position of the head of the stitch alternates between subsequent wales. The horizontal parts (along the course) of the stitches can be regarded as those making up the traditional parts of a helical coil. These do not change much between the different stitch implementations. The difference is in the crossover points between the legs of the stitches (this is well illustrated in the 3D stitch images in [15]). Looking into the equation for the self-inductance of a thin wire with random geometry, as given by [16]:

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

with a the wire diameter, s measures the length along the wire axis and μ_0 the permeability in vacuum, gives an insight into the possible reason for the difference in inductance. The term $|x_1 - x_2|$ in the denominator of eq. (1) signifies a large contribution of the geometry at the crossover points where $|x_1 - x_2|$ becomes small. Thus it is expected that the local geometry at the crossover points of the legs of the neighbouring stitches along the course and/or wale, play an important role in the final inductance of the knitted coil.

While lace (Fig. 5 a1 & a2) does decrease the resistance slightly, using multiple thin wires (c1* & c1**) or using jacquard (b1, b1* & b2) leads to better decrease in series resistance, with b2 giving the lowest resistance. Table 1 shows that all approaches to reduce R_s also reduce L. In comparison with the jacquard implementation, the higher L in the standard stockinette (Fig. 3) is due to the heads of each stitch in neighbouring courses being at half a distance of the stitch height. In the jacquard implementation this close separation disappears when the floating stitches – horizontal lengths of wire that are un-knitted but elongated behind the work – are separated over the full stitch height (see supplementary information S2). These implementations also lead to reduced elasticity of the knit.

The influence of the series resistance is to decrease the quality factor, Q of the knitted coil. Calculated values of $Q = \omega L/R_s$ are shown in Fig. 6 for a frequency f = 100 kHz.

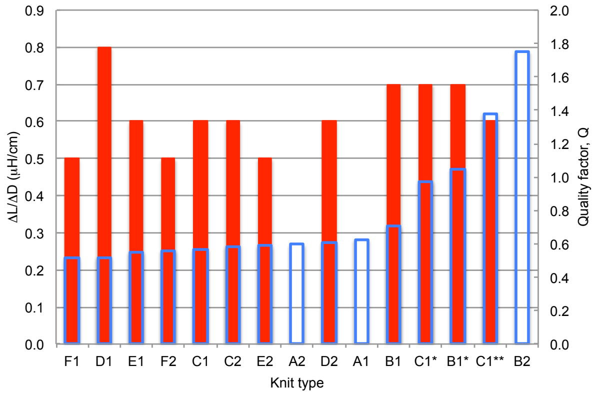

Figure 6: The quality factor of the different knits (open blue rectangles) and the sensitivity (closed red rectangles). The knit types are given in Fig. 5. The knit types are in increasing order of Q. No sensitivity is given for knits with poor elasticity.

Fig. 6 also gives the sensitivity – the variation of the inductance as a function of diameter of the coil, $\Delta L/\Delta D$. These values are obtained from linear fits to the measurements in Table 1. Fig. 4 illustrates good linear fits for the viscose yarn, representative for the other measurements. The results of those samples that could not stretch to 95 mm, are not given. The highest variation is obtained for the stockinette in elastic yarn. However, the best knit is potentially C1** which is the cotton stockinette stitch in 3 mm yarn but with 3 thin Cu wires knitted together. This maintains a relatively high self-inductance but reduces the resistance significantly leading to higher Q. This result is not surprising as multiple thin Cu wires connected in parallel decrease the resistance. To improve on this, Litz wire [17] could be used that would also improve flexibility.

3. Study of the inductance of an integrated knitted coil in a baby romper

In this section we study the knitted coils in a romper suit (see Fig. 2c) [18] for simulated breathing measurements. The body of the suit is knitted in the round with 3 mm needles and is 8 cm long and ~50 cm in circumference. It contains two knitted coils with N = 5, one at abdomen and one at thorax level. The distance between the coils is large enough to allow each coil to function independently. The body of the suit was knitted using elastic viscose and cotton yarn in both stockinette and 1/1 rib (the garter stitch was not used as this tends to also stretch in the length of the garment). As with the cuffs, the variation of the self-inductance as a function of diameter in a region of $14 \leq D \leq 17$ cm, is linear (see supplementary material S3). The self-inductance of the rib is higher than that of the stockinette for both yarn types, consistent with the results for the cuffs. The variation of the self-inductance with diameter is $\Delta L/\Delta D$ = 0.68 μH/cm for both stockinette and rib in cotton yarn. $\Delta L/\Delta D$ = 0.72 μH/cm for rib and $\Delta L/\Delta D$ = 0.84 μH/cm for stockinette in elastic viscose yarn. The higher values of $\Delta L/\Delta D$ for the elastic yarn are also consistent with the findings for the cuffs. The hypothesis is that the easier it is to stretch the garment, the better $\Delta L/\Delta D$. This conclusion is only valid if the elongation of the garment is limited by the 3D yarn rather than by the 1D thin Cu wire.

Small variations of the number of stiches for the same stitch type, yarn and diameter do not change the sensitivity. The body of the cotton romper suit is knitted with 110 stitches in the round. If this number of stitches is increased to 118 or reduced to 92 then we find, for the same diameter of the "body" supporting the knitted suit, that the self-inductance is higher with a higher number of stitches but that the value of $\Delta L/\Delta D$ remains the same in all cases as long as the number of stitches allows the required stretch (see supplementary material S3). The 92 stitches suit does not stretch to the same diameter as the others, reducing $\Delta L/\Delta D$ from 0.68 μH/cm to 0.37 μH/cm. Finally, a balloon was used to simulate breathing. By pressing on the balloon, its circumference was varied between 44 cm (below which the suit slides down the balloon) to 53 cm where a stretch of the garment is obtained without deforming the knit. A 9 cm variation in circumference is much larger than the abdomen circumference variation of a healthy, sleeping infant during breathing which is ~3 cm [19]. A 3 cm variation in circumference translates into an inductance change of ~0.6 μH in the romper knit. Fig. 7, for the viscose yarn implementation, confirms that the variation in inductance obtained from the rib is smaller than that obtained from the stockinette stitch for the same diameter change. The measurements also show a lack of hysteresis for the rib and small hysteresis for the stockinette for this short time use. It might be argued that rib is preferable for reducing hysteresis as this knit type pulls the garment back to its original size after stretch.

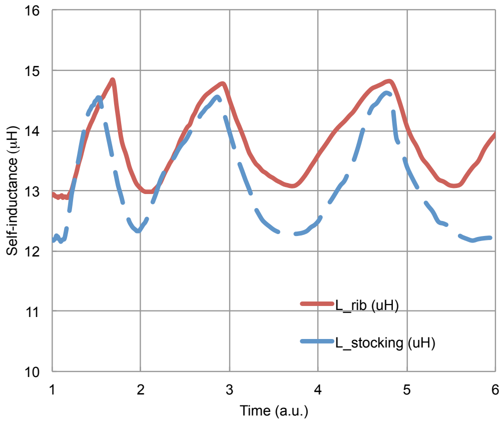

Figure 7: 3 simulated in- and exhalations changing the diameter of the romper suit (elastic viscose) by ~3.5 cm. Full line (red): rib and dashed line (blue): stockinette.

4. Conclusion

Thin insulated Cu wire was knitted in the round together with classical yarn. This knit behaves as a helical coil with an inductance dependent on diameter of the knitted cylinder and the number of rows in which the Cu wire is integrated. Stretching the diameter of the knit increases its self-inductance while the resistance remains constant. It was found that rib stitch has a higher self-inductance than stockinette for all yarn types. It is hypothesised that the difference in geometry of the crossover points between neighbouring stitches in the different knit styles has an impact on the value of the self-inductance of the coils with the same diameter and number of turns. Although using thicker yarn results in a longer coil, the self-inductance and variation of the inductance with diameter was found to be similar as for thinner yarn.

Lace, jacquard and multiple thin Cu wires were used to reduce the resistance. It was found that all these implementations also reduce the self-inductance and tend to decrease the elasticity of the garment. The conclusion is that metals such as Litz wire, consisting of multiple thin metal wires in parallel, might be the best option to conserve flexibility while maintaining a good quality factor.

A baby romper suit was knitted with two integrated knitted coils in stockinette and rib and in two different yarns, cotton and flexible viscose. The stockinette stitch of a baby romper suit in elastic viscose shows the highest sensitivity: $\Delta L/\Delta D$ = 0.84 μH/cm. A small ~7% increase or decrease in number of stitches changes the self-inductance but not the sensitivity unless the starting diameter is too small to allow the body to stretch freely.

This work shows that knitted coils integrated in wearable and comfortable garments can be used for continuous monitoring of health signals such as e.g. breathing. Other applications could be measurement of e.g. edema in legs [20] or stress measurements in e.g. military personnel.

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