Electromagnetic Yarn: an Improvement over Current Textile Actuator Technology?

New Textiles Report by Sarah Bates

In this report we document the optimization of a proposed textile actuator and a comparison between it and the most widely used actuator in use in e-textiles today: muscle wire.

Yarn lends itself well as a carrier for electromagnets given its linear twisted form. When taut, it looks identical to soft core solenoid electromagnets. When unloaded, the electromagnet approximates the flexibility of the original yarn itself. We have already prototyped a first concept of the electromagnetic yarn. Figure 1 illustrates the first attempt consisting of 2 cm bundles (150 turns) of copper wire followed by 2 cm of cotton. The spacing between bundles allows for flexibility as well as giving the yarn the appearance of copper beading. The prototype produced a .001 T field with .57 amps of current across a voltage difference of 15.3 V. It was attracted to a Neodymium magnet with a remnant magnetic field of .5 T.

In this report we will weigh four competing factors: magnetic force across a distance, weight per unit length, energy consumption, and aesthetic.

Figure 1: A prototype of a simple electro magnetic yarn

Modeling of a Simple EM Yarn

To begin we model the simple yarn already prototyped. We can do this by applying the law of Biot Savart to find the magnetic field at a point a distance x from the center of the solenoid on the axis of a solenoid of radius r, with N turns, and a current I running through it. This leads us to Equation 1:

$$B_x = \frac{\mu_0 N I r^2}{2(x^2 + r^2)} \qquad \text{Eq. 1}$$

The permittivity of air is μ_0 known to be equal to $4\pi x10^7$ Tm/A. Note that the field is maximum at the center of the solenoid when $x = 0$. Inserting the measured values for the fabricated coil, where $N = 150$, $r = 1$cm and I is .57 A we find the B field to be equal to $5x10^{-5}$ which is within a factor of 20 of the measured value.

The field is considerably weaker outside of the coil where we would likely place any magnets involved in actually actuating the yarn. The highest fields along the length of the solenoid are inaccessible as the cotton the copper is wound around occupies this space. We will discuss the potential for redesign based around this point in a later section.

Because we cannot find an analytical expression for the field outside of the coil, we use a finite element package to solve for this field. The results of this simulation are included in the figure below. The light green area is approximately equal to the measured field just outside the coil.

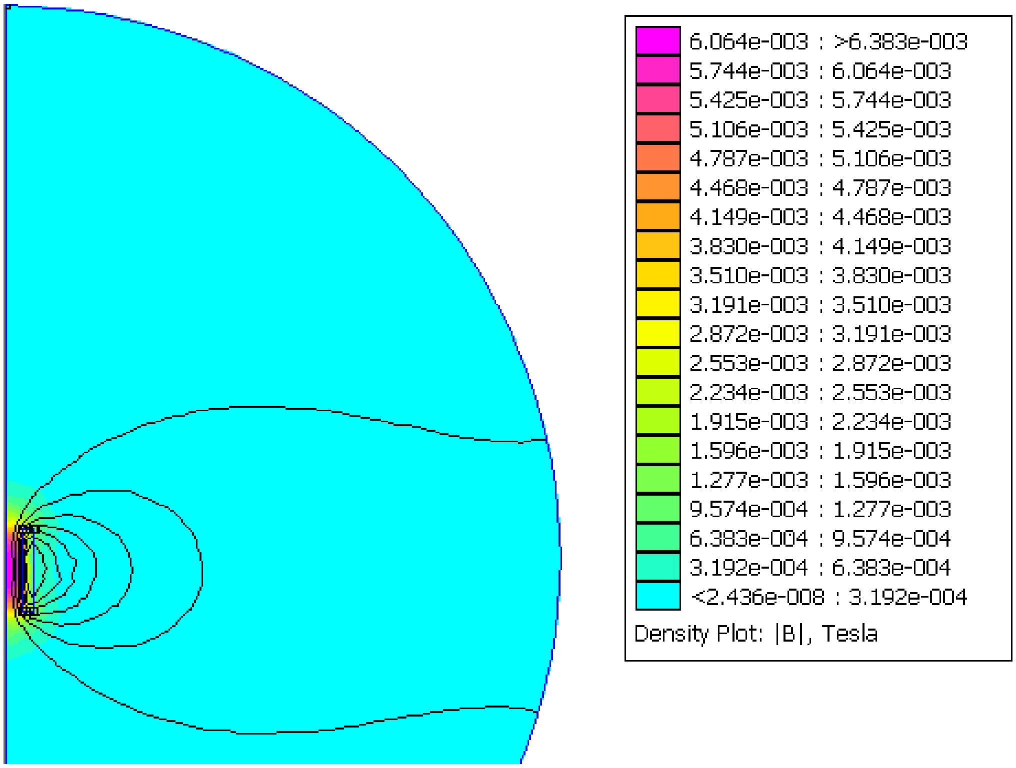


Figure 2: The B field of a 2D slice of the coil modeled in FEMM

First Improvements: Iron core and Orientation

The previously modeled yarn had a cotton core which we approximated as an air core because of cotton's low permeability. By simply replacing the cotton with steel wool or silicone with carbonyl iron we can change the magnetic field by orders of magnitude. The relative permeability (compared to air) of steel is 100, while carbonyl iron is estimated as having a relative permeability between 7 and up to 150 (the lower value for iron powder, the higher value for 99% pure iron). We can estimate the effect of these cores by multiplying the above plot by the relative permeability. This leads to a field of between .007 T and .01 T depending on material choice.

In addition to a magnetic core, we will reorient the coil so that the axis of the coil is not along the yarn but rather perpendicular so that the iron core is directly exposed to air. This way the area of largest field may interact with the magnet, leading to a larger force exerted on the solenoid. To calculate this force we begin by approximating the solenoid and the permanent magnet as infinite magnetized surfaces.

$$F = \frac{B_{rem} A B_{solenoid}}{2\mu_0} \qquad \text{Eq. 2}$$

In actuality, we must account for the fact that the solenoid and magnet each have two surfaces that interact, both their N and S ends, which repel (because of N,N and S,S) as the two objects are attracted to each other (by the N, S and S,N). The thicker the solenoid and the magnet are the more the surface approximation holds true. Inserting the equation of a solenoid (with relative permeability k) into the force equation above we see that the force also has a dependence on the interaction distance (x) and other features of the coil.

$$F = \frac{B_{rem} \pi r^4 k N I}{4(x^2 + r^2)} \qquad \text{Eq. 3}$$

We have taken the area (A) in the Equation 2. to be the area of the solenoid.

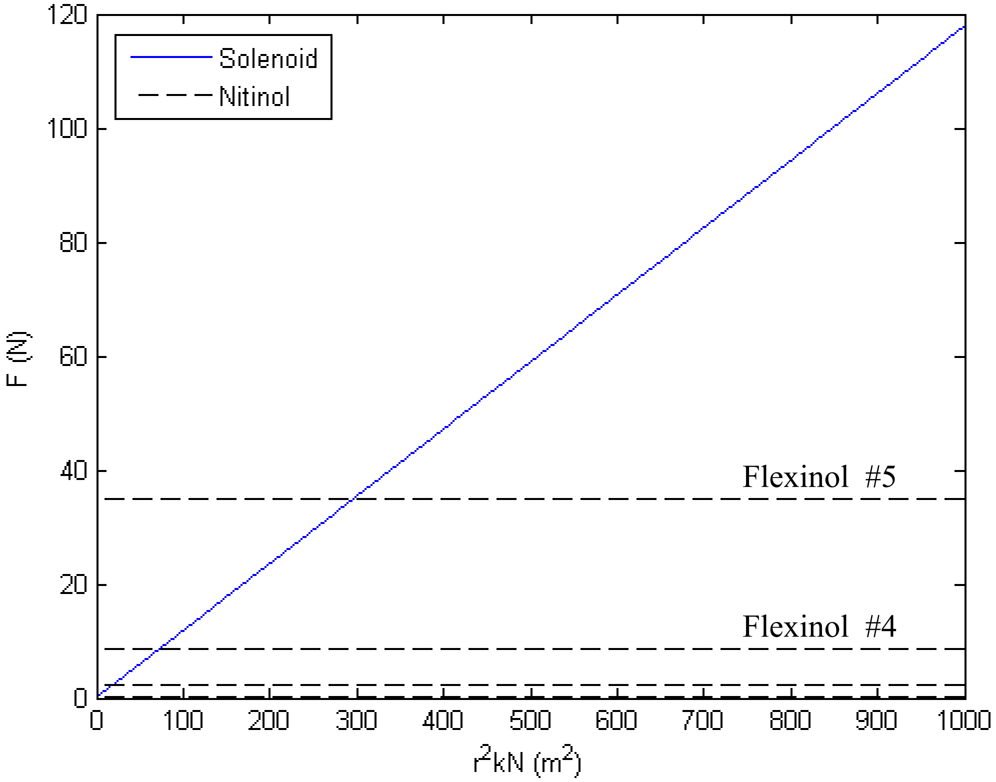
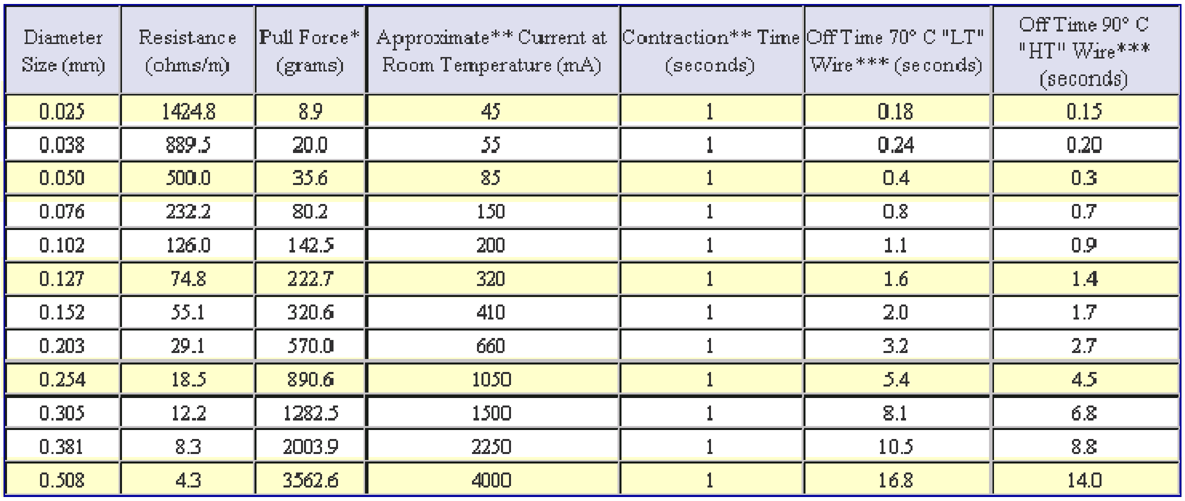


Figure 3: The force (taken infinitely close to the center of the solenoid) generated by a solenoid as a function of the product of the relative permeability, the number of turns, and the radius squared. This force can be compared with the force of several available nitinol wire products which given by black lines for reference.

As can be seen from Figure 3, with a large, iron core, many turned coil, we can generate more force than nitinol wire products detailed in Figure 4.

Flexinol Technical Design Specifications



	Diameter Size (mm)	Resistance (ohms/m)	Pull Force* (grams)	Approximate** Current at Room Temperature (mA)	Contraction** Time (seconds)	Off Time 70° C "LT" Wire*** (seconds)	Off Time 90° C "HT" Wire*** (seconds)
1.	0.025	1424.8	8.9	45	1	0.18	0.15
	0.038	889.5	20.0	55	1	0.24	0.20
2.	0.050	500.0	35.6	85	1	0.4	0.3
	0.076	232.2	80.2	150	1	0.8	0.7
	0.102	126.0	142.5	200	1	1.1	0.9
3.	0.127	74.8	222.7	320	1	1.6	1.4
	0.152	55.1	320.6	410	1	2.0	1.7
	0.203	29.1	570.0	660	1	3.2	2.7
4.	0.254	18.5	890.6	1050	1	5.4	4.5
	0.305	12.2	1282.5	1500	1	8.1	6.8
	0.381	8.3	2003.9	2250	1	10.5	8.8
5.	0.508	4.3	3562.6	4000	1	16.8	14.0

http://www.dynalloy.com/TechData_Metric.html

Figure 4: Nitinol products available under the trade name Flexinol. The highlighted entries are used for comparison through out this report.

Design of yarn for loading

As we begin to look into designing the radius(r) and the number of coils (N), we look to other constraints besides maximizing the force. Based on our design of sowing the yarn into the hem of a garment, the force between the two elements should be able to lift the yarn's weight. The weight of the coil and the core is given below in Eq. 4:

$$F_{mg} = (2N\pi^2 r r_w^2 \rho_{dw} + \rho_{dc}\pi r^2 2 r_w N)g \qquad \text{Eq. 4}$$

Note that we have modeled the core scaling with the radius and the number of turns.

We wish to maximize the ratio of the magnetic force (taken at the center of the coil x=0) to the force of gravity:

$$\tilde{F} = \frac{B_{rem} r k I}{8\rho_{dw}\pi r_w^2 g\left(1+\frac{r\rho_{dc}}{\pi r_w \rho_{dw}}\right)} \qquad \text{Eq. 5}$$

We can see that the weight of the core is larger than the weight of the solenoid and therefore this ratio is approximately constant. Given that we know the current limitation is approximately .3 Amps for 32 gauge wire, we can see that what k, r, and B must be to have this ratio be equal to 1. For an air core solenoid the radius would need to be .15 meters, prohibitively large. For a steel core, we calculate that the product of B_{rem} and k must be 200 for the yarn to lift its own weight. Since the available magnet has a remnant field of .5 this puts k outside of the available rage. Therefore we will look to reduce the density of the core by using a blend of steel wool, silicone and carbonyl iron. By significantly lowering the density, we can bring the parameters into a reasonable range of k = 120.

We can plot the force generated normalized by the weight for air core solenoids versus metallic core solenoids as a function of r.

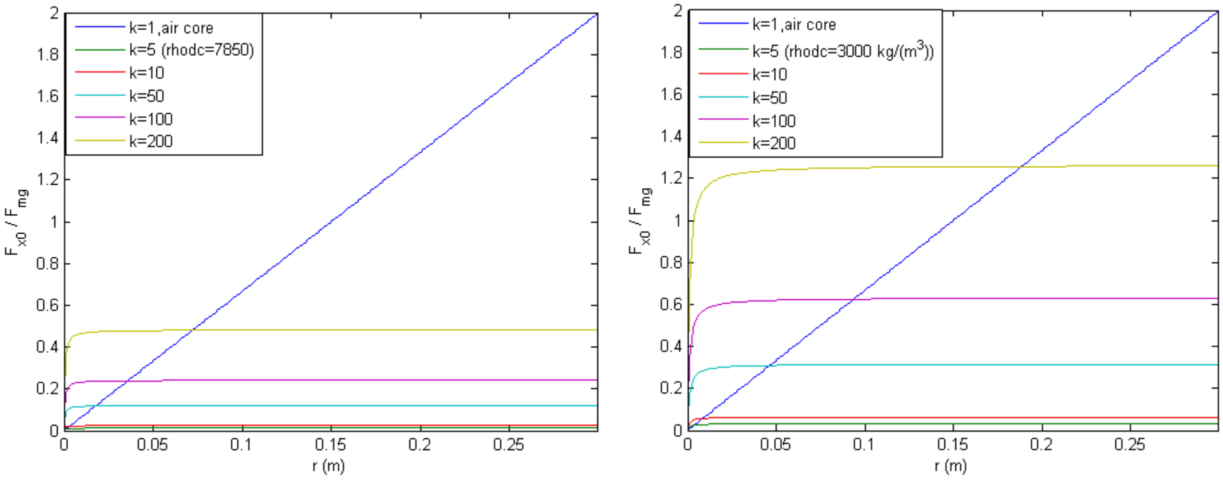


Figure 5: The two graphs compare the force ratio as a function of coil radius for varying core materials. The left graph assumes the core to be solid steel while the right graph a material with a lower density.

This leads us to conclude that large air core electromagnets are appropriate if we are to lift the yarn. However it may be more prudent to abandon this design for one in which the electromagnet is stationary and we wish to move another component either the permanent magnet itself or a ferromagnetic latex.

Alternatively we could pursue designs where the solenoid's core is fixed at a given size to limit its impact on the coil's weight changing the force ratio to:

$$\tilde{F} = \frac{B_{rem} r^2 kNI}{8N\pi r_w^{\ 2} \rho_{dw} g(Nr + C)} \quad where \quad C = \frac{\rho_{dc} r_c^{\ 2} h}{2\pi \rho_{dw} r_w^{\ 2}} \qquad \text{Eq. 6}$$

This is scenario more realistically models traditional solenoids.

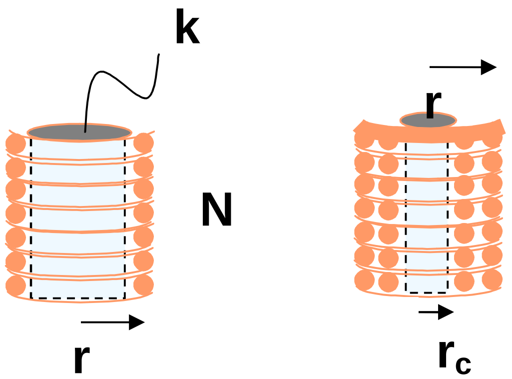


Figure 6: Illustration of core size which varies with solenoid radius, and core size which is fixed.

We therefore briefly investigate whether our analysis is consistent with available information about current solenoid technology.

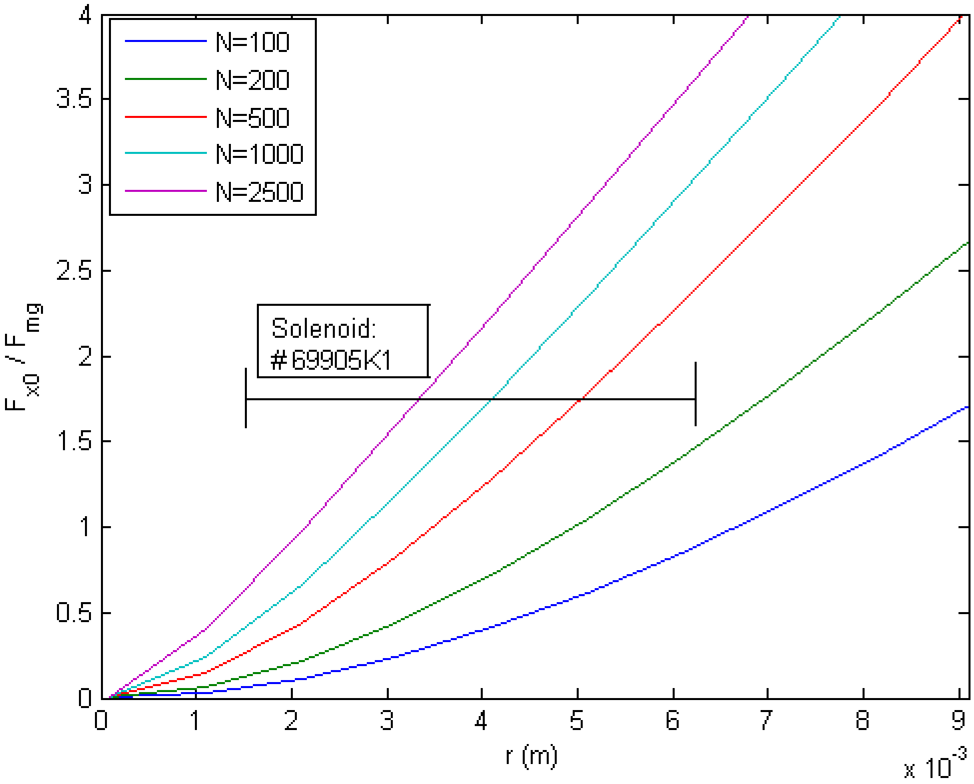
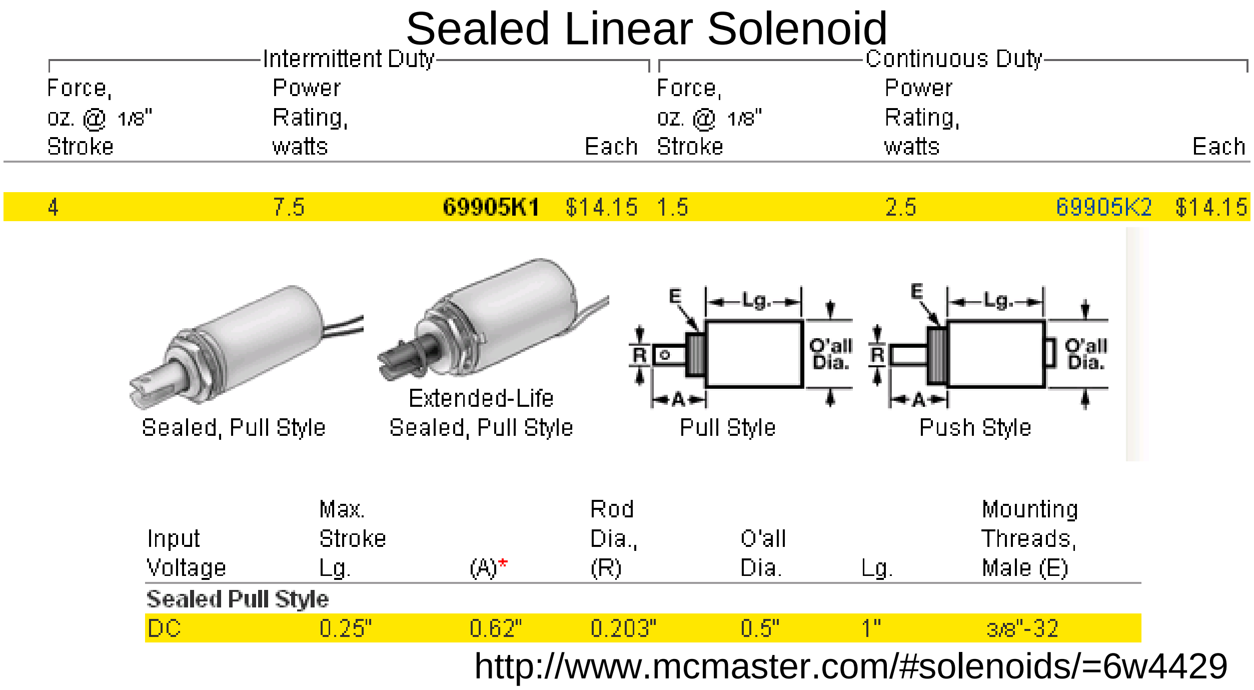


Figure 7: The force ratio as a function of solenoid radius of a solenoid with a fixed core size. This limits the total contribution of the core to the solenoid's weight.

In the above graph we have limited the core to a 2.54 cm height and a .26 cm radius. We have assumed a value of 100 for the relative permeability and a current of 20 mA. This approximates the smallest sealed linear solenoid purchasable from McMaster. Given the technical specifications given for a continuous cycle, we calculate that the ratio between the generated force and the weight force is approximately 1.7. We also calculate that the maximum number of turns possible to fit within the solenoid casing given 32 AWG wire is 2500. We can see that the force ratio we calculate from Equation 6 is very close to the one calculated from the published data. This validates our current model. Note that we can now achieve lifting with a more reasonable radius. For radii larger than the assumed core radius, more creative manufacturing techniques may need to be applied.



Sealed Linear Solenoid

Intermittent Duty				Continuous Duty			
Force, oz. @ 1/8" Stroke	Power Rating, watts		Each	Force, oz. @ 1/8" Stroke	Power Rating, watts		Each
4	7.5	**69905K1**	$14.15	1.5	2.5	69905K2	$14.15

Sealed, Pull Style

Extended-Life Sealed, Pull Style

Pull Style

Push Style

Input Voltage	Max. Stroke Lg.	(A)*	Rod Dia., (R)	O'all Dia.	Lg.	Mounting Threads, Male (E)
Sealed Pull Style						
DC	0.25"	0.62"	0.203"	0.5"	1"	3/8"-32

http://www.mcmaster.com/#solenoids/=6w4429

Figure 8: Product specifications of solenoid compared to a fixed core size yarn.

For comparison this ratio is much larger (estimated to be over 10^9) for Nitinol wire given its light weight. This also leads us to consider designs where the electromagnet remains fixed as the EM yarn does have an advantage in terms of pure force generation over the Nitinol.

Estimate of power consumption

Another consideration is the power consumption of the electromagnetic yarn. The power consumption of the electromagnet is given by Eq. 7

$$P = I^2 \frac{\rho_{rc} N 2r}{r_w^2} \qquad \text{Eq. 7}$$

Therefore the power consumption is given in the following graph as a function of the size and number of the loops in a single coil.

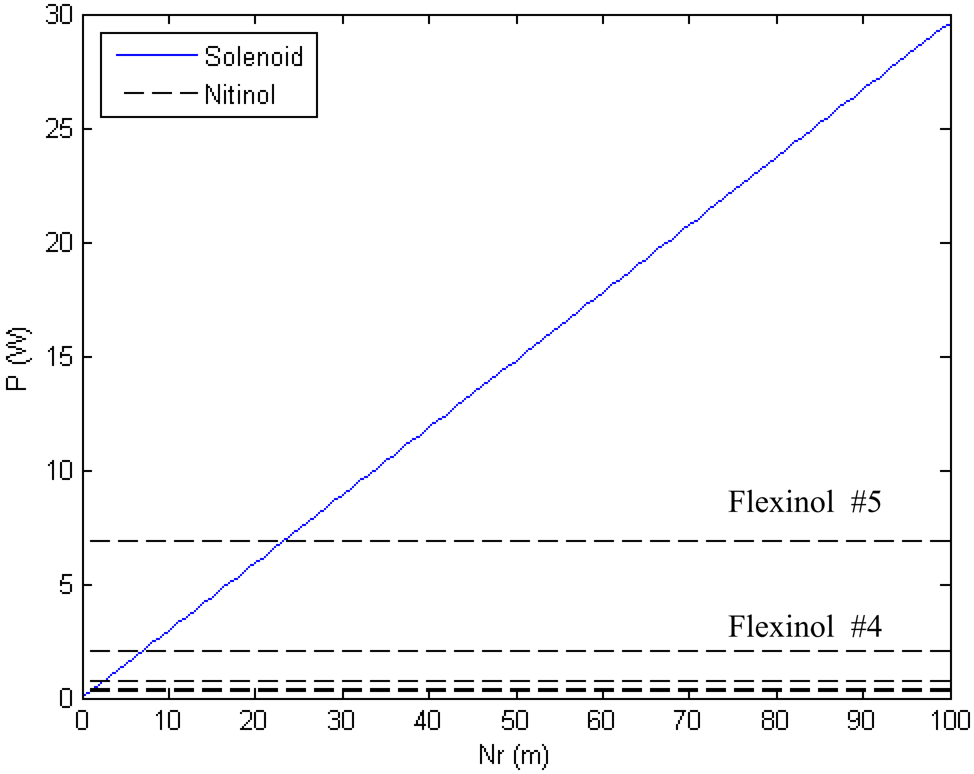


Figure 9: The power consumed by an electromagnet with a radius of r and N turns.

To compare Nitinol wire to the EM yarn we should compare the force generated per energy consumed. This number is

$$\frac{F}{P} = \frac{B_{rem} \pi r^4 k r_w{}^2}{4(x^2 + r^2) \rho_{rc} 2rI} \qquad \text{Eq.8}$$

For applications where taking the interaction distance of zero is appropriate (x=0). We can plot this and compare it to the consumption of Nitinol:

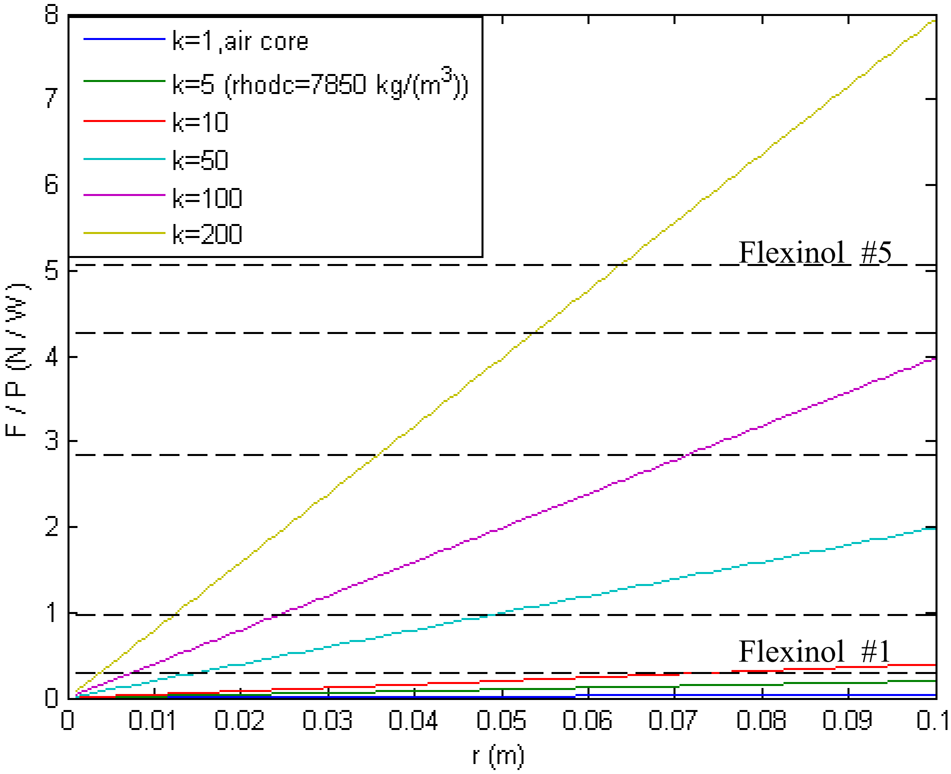


Figure 10: The force generated per power consumed as a function of solenoid radius for the electromagnetic yarn.

Note that larger coils are a considerable improvement over nitinol wire. Even smaller coils are better when compared to nitinol products with similar current demands.

Conclusions and Recommendations

Both measures of actuating force normalized by weight and force by power consumption seem to indicate that electromagnetic yarn is not a clearly better technology over nitinol wire in the context of textiles. It can develop larger forces if not required to lift its own weight. In general we have not taken interaction length into account, but have provided methods to evaluate the force. Finding higher permeability fibers would provide a key improvement to the feasibility of EM yarn as an actuator. Mu-metals (a nickel iron alloy) would have a large impact on this analysis and would suggest that the EM yarn may still dominate as a textile actuator. EM yarns still hold an advantage over nitinol in their fast cycle times, lower currents, and limited hysteresis.

Many mechanisms can be built exploiting the advantages (such as weight, wireless, etc) of the electromagnetic yarn. One such mechanism is suggested in figure 11. Others involve ferromagnetic silicone although the force will be much smaller given the absence of a permanent magnet.

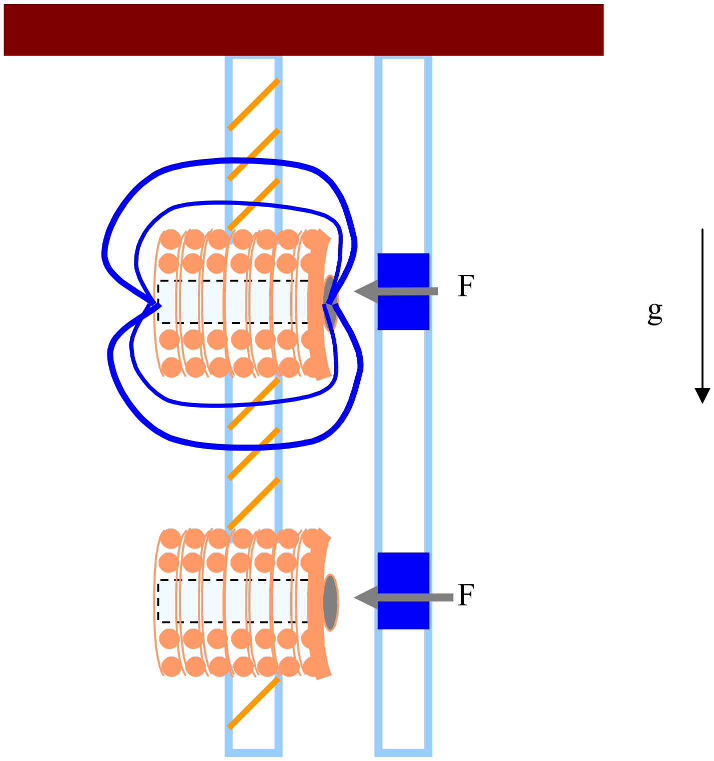


Figure 11: Hanging tassels mechanisms: when the electomagnets are turned on the permanent magnets exert an attractive (or repulsive) force; when off the tassels return to their original position.