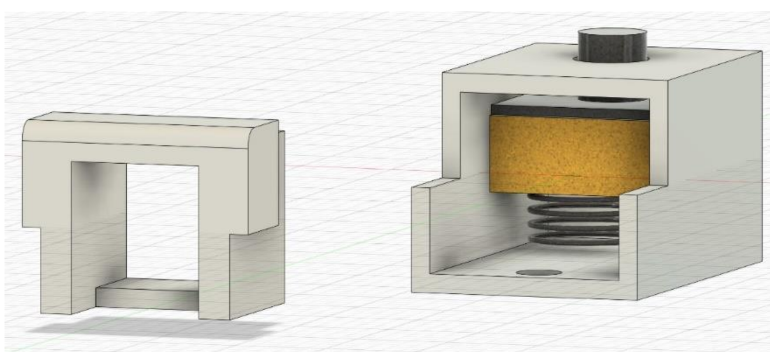
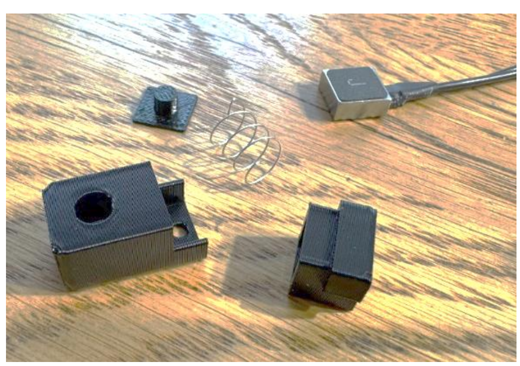
Design Considerations for LRA Tactors

Introduction

What follows is a description of the theoretical design criteria that were considered in designing a tactor housing for a square shaped z-direction LRA. Detailed instructions and 3D print files for constructing tactors and fitting them to a glove are provided with the Buzzah neck build instructions. While I developed this tactor housing to use in my Buzzah Neck Build, but it would work in any LRA-based design.



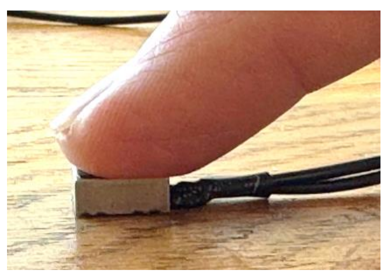


Physical Principles of LRA Tactors

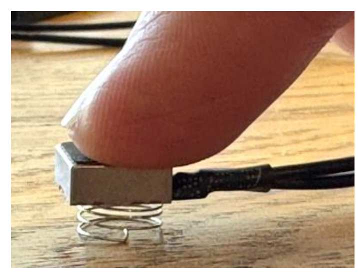
Imagine a paint can that is vibrates inside a shaker case as shown here. When the case pushes up on the can, Newton's 3rd law tells us that the case must experience a downward reaction force from the paint can. This downward force on the case does not create any motion of the case because the case is "grounded" on a table which does not allow motion in the downward direction. However, when the case alternatively pushes downward on the paint can, the inertia of the can results in an upward force on the case. If this upward force from the can is greater than the weight of the case, the case will be lifted off the table. The scenario just described is exactly analogous to what is going on in an LRA vibrator that is being driven by a Buzzah driver. Instead of having a paint can, the LRA has a relatively massive magnet that is vibrates up and down inside its case, resulting in the vibrations of the case we observe externally.

To illustrate the challenges of tactor design for an LRA, consider the following demonstration. In (A), a vibrating LRA vibrates vigorously off a table like the paint shaker our previous example. In (B), a finger pushes gently downward on the vibrating LRA. If you were to perform this experiment yourself, you would find that the LRAs vibration is quickly grounded out by the table, even with only a very slight pressure from your finger. However, if a weak spring is placed between the vibrating LRA and the tabletop as in (C), you would find that the LRA continues to vibrate vigorously up and down as long as you don't push so hard as to completely compress the spring against the tabletop. As we design our tactor, we must likewise incorporate an elastic element within our tactor housing that allows a free up and down LRA vibration as in (C).

(A)

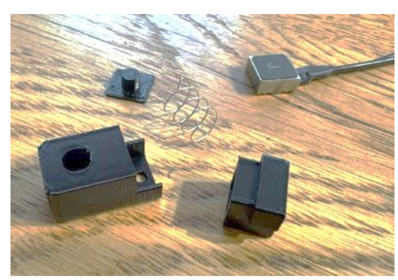


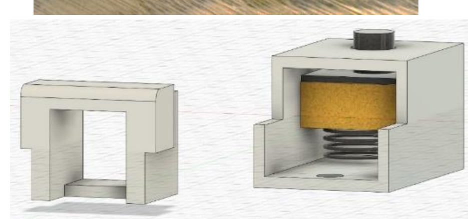
(B)

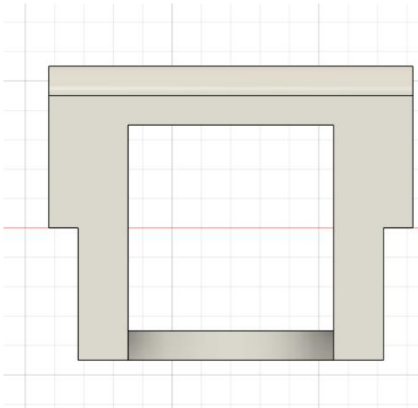


(C)

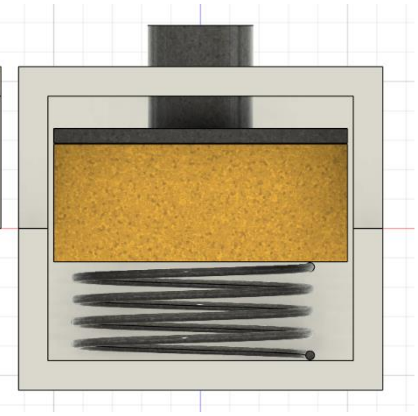
The 5 elements of the LRA tactor I designed are illustrated here. The LRA buzzer is sandwiched between a button plunger from above, and a weak spring from below. When the button is depressed, the internal plunger is pushed away from the top of the tactor housing. This keeps the LRA from mechanically grounding out to the top of the case which is itself grounded by the glove finger elastically holding the case against the fingertip. The LRA vibrates freely within its rectangular enclosure that is closed in by the endcap which is held in place by a tight friction fit. No fasteners are required. The endcap fits tight enough not to loosen from normal use, but not so tight that it cannot be removed with needle nose pliers. The window in the endcap is big enough to allow the electrical leads to exit, but small enough to keep the LRA and spring from vibrating out of their box inside the case. The hole in the bottom of the case allows the tactor to be attached inside a glove using a small plastic wire tie.



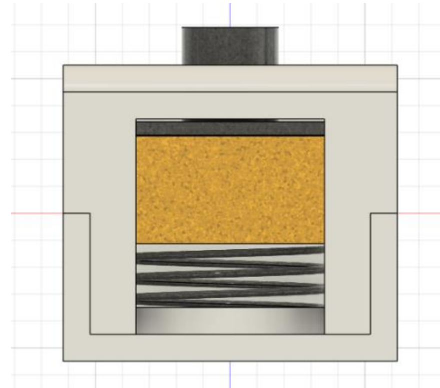




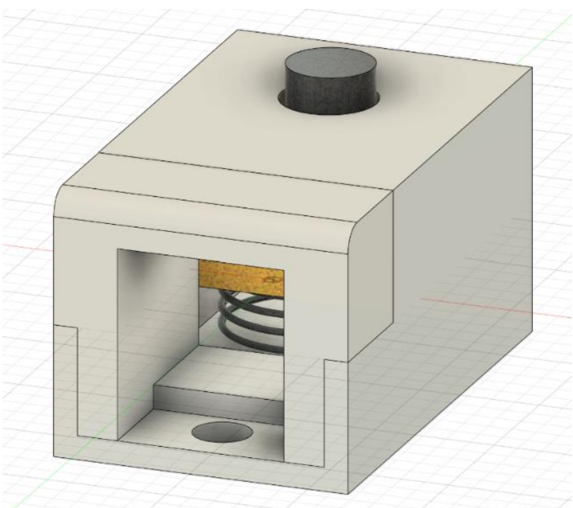
Endcap

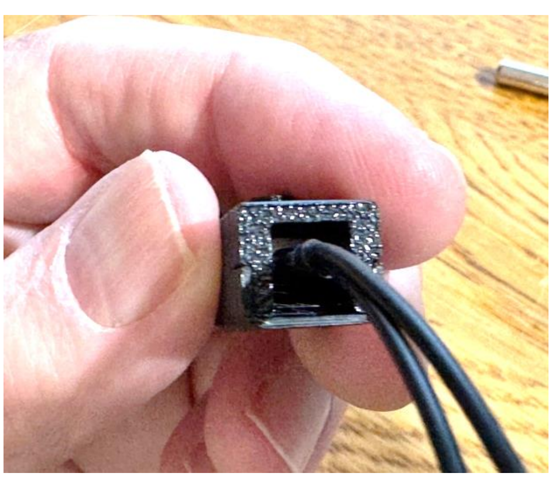


Open end of case without endcap



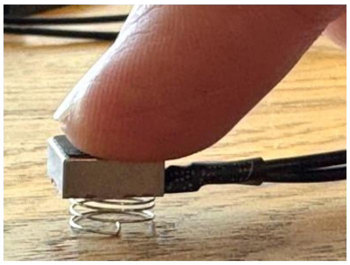
Endcap holding components in case



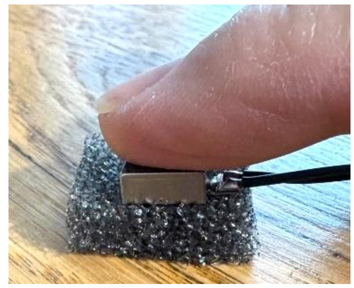


Determining Spring Characteristics

Before deciding to employ a spring to decouple the LRA from the tactor enclosure, I tried various types of springy foam and sponges collected from around the house and from various hardware store products. But all samples damped the vibration of the LRA to unacceptable levels. One can easily observe the damping effect that is introduced by foam by performing this simple test: In figure (A), a buzzer is hooked to an LRA driver and decoupled from the tabletop using a weak spring of length 11 mm. The buzz that is experienced with the spring is then compared to the same buzzer decoupled from the tabletop by foam with 11 mm thickness as we see in figure (B).



(A)

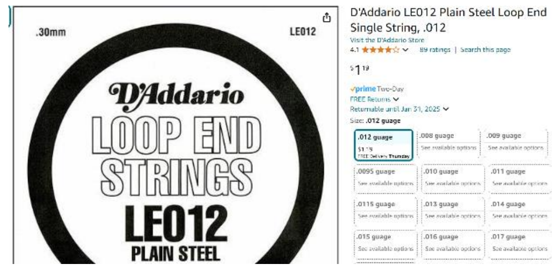


(B)

When I performed this test, I found that the foam significantly damped the motion of the LRA buzzer compared to the spring. With the spring, the perceived buzz amplitude felt uniform, with no change in amplitude as I increased loading force as per Tass specifications to achieve the required 0.5 mm preload skin indentation. However, the foam gave a highly non-linear response, with perhaps 20% damping compared to the spring for very light preloading, and well over 50% damping for stronger preloading. There are two properties of the foam that caused this. First, all the foam I could find was too stiff, creating too strong coupling with the table, thereby grounding out vibrations. The stiffness of the foam appeared to increase non-linearly with increased deflection, leading to an observed rapid increase in damping at higher preloading. One might think we could solve the grounding problem if we could just find weaker foam. However, foam has another problem: It is inherently inelastic. Imagine trying to bounce a ball on foam and you realize the ball barely bounces because of the foam is eating up energy internally through damping. So, even if we could find a foam that feels sufficiently cushy, it would still be problematic due to its inherent damping characteristics.

Finding a sufficiently weak spring with the proper dimensions as shown in figure (A) was a challenge. There are plenty of springs on Amazon that are the right size, but they were all way too strong for this application, creating too strong coupling between the tactor housing and LRA. Suppliers online such as https://www.thespringstore.com/ advertise 70 trillion springs available. However, 99.9999% of their springs are only available by special order, outrageously priced at $4-$10 per spring. Still in my design phase, I was still not sure about the ideal spring force constant, wire diameter, coil diameter, number of turns, and coil pitch, so special ordering high priced springs for testing was not a viable option. Then my wife suggested I make my own springs. It turns out they are very easy to make as illustrated here on YouTube: https://www.youtube.com/shorts/M9Lnm1P6_70 . After experimenting with the many parameters by trial and error, I finally settled on the criteria discussed below.

Wire type



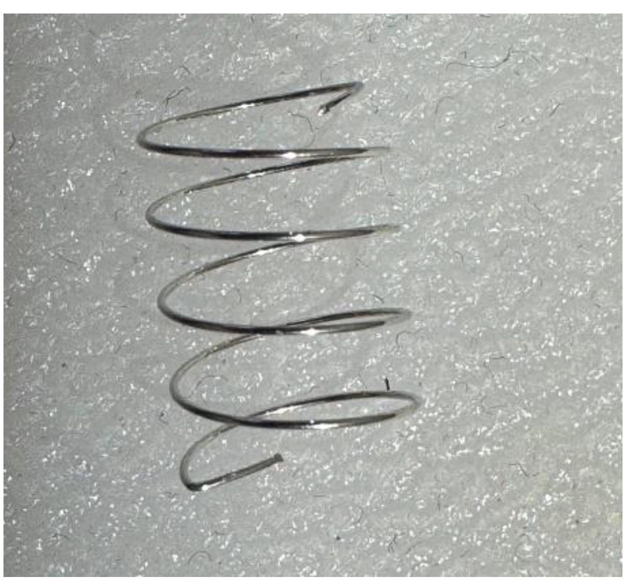
Once I had the idea to make my own springs, I quickly found that guitar strings were ideal for this purpose because they are cheap and come in many gauges. Looped end guitar string of diameter 0.012 inch proved to be idea. Each string makes up to 7 springs, but I would suggest buying 10 strings so you have plenty to for practice – total cost $11.90 on Amazon.

Rod Diameter

The coil expands quite a bit after unwinding from the rod. <u>And different gauge wire expands to make different diameter coils</u>. Through trial and error, I found that 0.012-gauge wire yields a perfect spring diameter of 8.5 mm when wound and released from a 3/16" steel rod. An 8.5 mm diameter coil fits nicely under the 10 mm square LRA, and it is big enough that it does not vibrate out the wire window in the tactor. The rod can be purchased from Home Depot for $3.92 (see tools list). Note that the rod comes coated with very dirty oil and you will need to wash it and cut it down to about 18 inches before you start making springs.

Number of Coils

There are two factors to consider in determining the optimal number of coils to use in springs. We don't want to have too many coils because, when the button is fully depressed, the compressed coils start taking up too much space in the bottom of the enclosure and can bottom out. Alternatively, having too few coils leads to too large of an angle between the spring and the LRA bottom which can cause binding in the chamber. After much experimenting, I ended up settling on the optimal number of coils to be 4.5. Having the half-coil on the end helps keep the spring from canting during use. As you see in the pictures shown below, I also put a small bend on either end of the spring to keep the ends from snagging and slipping up the side of the LRA.



Skin Preloading Displacement and Spring Rest Length

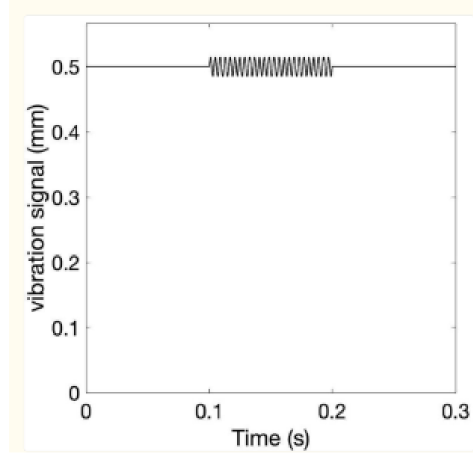
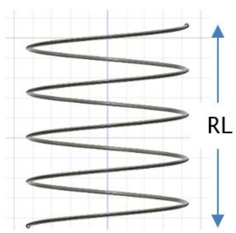


Figure 3. Vibratory burst at 250 Hz.

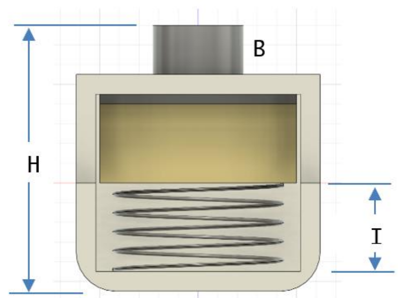
The crucial parameter of skin preloading displacement is perhaps the most important adjustable parameter of the tactor since it relates most directly to the quality of the vibration sensation that the tactor imparts to the fingertip. I accordingly spent a lot of time making sure I matched Dr. Tass's specifications for this parameter as closely as possible.

In the diagram shown at right, we see the ideal 250 Hz tactor vibration signal that is to be applied to a fingertip in the Tass specifications from his device specs paper: https://pmc.ncbi.nlm.nih.gov/articles/PMC5624565/ . The vibration signal consists of a small 0.03 mm amplitude vibration from the buzzer on top of a 0.5 mm preloading displacement. The preloading displacement is the distance the button contact protrudes into the skin when the tactor is mounted to a fingertip before the buzzer vibration is applied.

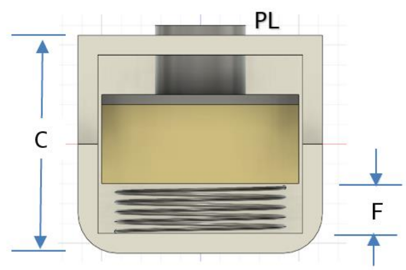
Consider the diagrams shown below to understand how preload skin displacement is achieved by our tactor/finger system through a balance between spring stiffness and skin elasticity. In (fig A), we see the spring at my ideal initial rest length, **RL** = 11 mm, which is coincidentally the same height as the case, **C**. In (fig B), the 11 mm spring is compressed to fit within case 4.5 mm cavity height, **I ,** that exists under the rectangular LRA before the button is depressed. In (fig C), the button is depressed by an unseen finger, further compressing the spring below to a length, **F**. The fraction of the button extending over the top of the enclosure, and thus protruding into the fingertip skin, is the ideal preload skin displacement, **PL** = 0.5 mm. Figure C then illustrates what the button should look like under the finger when a tactor is mounted to the finger.



(fig A)



(fig B)

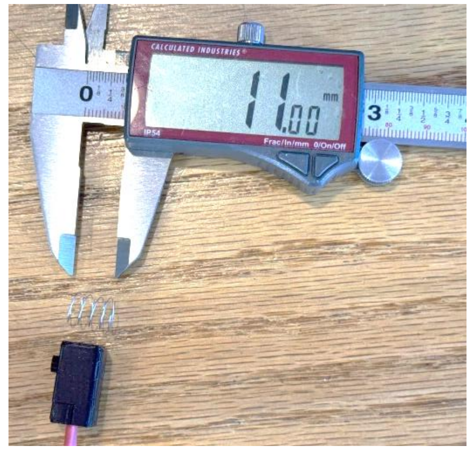


(fig C)

We see above that, since the button moves downward as the finger is positioned on the case, the preload skin displacement is not simply equal to the initial button height, **B**, above the case before the tactor is mounted to a fingertip. Instead, the preload skin displacement depends on the preloading force the spring exerts on the skin when the button is pushed. Since fingertip stiffness of the skin is much greater than that of the weak spring, most of the button travel is taken up by the spring, with only a fraction going into skin indentation.

<u>The variable in our tactor that controls the magnitude of preload skin displacement for our tactor is the spring stiffness</u>. As spring stiffness is increased, the preload skin displacement for a mounted tactor is correspondingly increased. The stiffness of a spring can be adjusted by small increments by changing its initial rest length. Stretching out a spring to have a longer initial rest length will make it stiffer. Winding a new spring with closer coils will result in a spring that is less stiff. If larger changes to stiffness are required, a new spring can be made with larger or smaller diameter guitar wire. Larger diameter wire

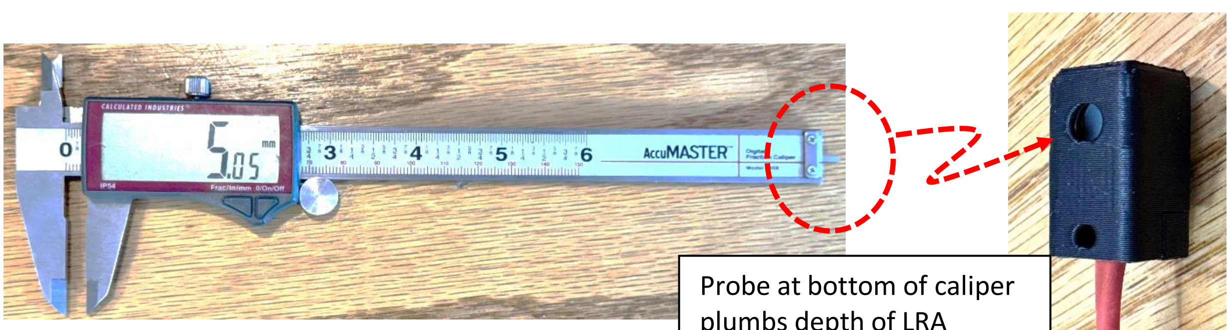
leads to stiffer springs. We nominally use 0.012” diameter wire, but guitar wire comes in all diameter increments from 0.009” to 0.022”. However, only the gauges from 0.011” to 0.013” are likely to produce springs in a useful stiffness range for our tactor. As discussed previously, if you want to experiment with different gauge wire, you may need to use a different rod diameter to end up with a useable spring diameter.



Since spring tension can only be modified with the spring outside the tactor housing, a process of trial-and-error testing must be undertaken to determine the ideal spring rest length and wire diameter for a particular user.

There are three methods I devised to measure the preload skin displacement resulting from a particular spring in a mounted tactor. In method 1, I simply adjusted spring stiffness by trial and error to achieve a subjective perception of a relatively light preloading force that produced a robust and localized “zing” sensation on my fingertips when the spring was in a tactor housing. Small changes in initial spring length result in significant changes in spring stiffness. If a spring is stretched to a longer initial length, the the preload displacement becomes greater, and the vibratory sensation increases. However, if a spring is too stiff, the vibrations cause finger bones to also vibrate which compromises therapeutic efficacy as Dr. Tass explains. If your spring is too strong, you need to make a new spring with closer coils and thereby less initial length. However, if a spring is too weak, therapeutic efficacy may also be compromised if the “zing” becomes too mild to clearly sense. <u>I therefore sought to maximize the zing without getting vibrations transferring into my bones</u>. Using the above trial-and-error method, I arrived at my ideal spring parameters of RL = 11 mm, number of coils = 4.5, and wire diameter = 0.012 inches.

While I was satisfied with the buzz sensation I achieved with these settings, I worried that my subjective method might not be yielding the proper Tass preload displacement of 0.50 mm. I therefore devised method 2, illustrated below, as an objective way to directly measure preload displacement and validate my subjective technique in method 1. In method 2, a special test tactor is 3D printed which has a 4 mm hole in its bottom surface. This hole in the bottom allows a feeler gauge to probe to the bottom of an LRA framed inside the assembled tactor. Note that two people are needed to perform this measurement.



Probe at bottom of caliper plumbs depth of LRA through hole in bottom

The difference in probe depth, before and after the tactor is mounted to a fingertip, yields the change in chamber height, I – F. The change in chamber height is likewise equal to the change in button height that occurs when the finger is mounted on the tactor.

$$Change\ in\ Chamber\ Height = \ Change\ in\ Button\ Height$$

$$I - F = B - PL$$

The tactor preload displacement, PL, is then found by,

$$PL = B - (I - F)$$

The initial button height, B, can be precisely found by subtracting the case height, C, from the initial overall tactor height, H,

$$Initial\ Button\ Height\ = \ Overall\ Tactor\ Height - Case\ Height$$

$$B = H - C$$

Plugging in the actual measurements I made on my test tactor using an 11 cm spring with 4.5 coils, I obtained,

$$PL = \quad H \quad - \quad C \quad - \quad (I \quad - \quad F)$$

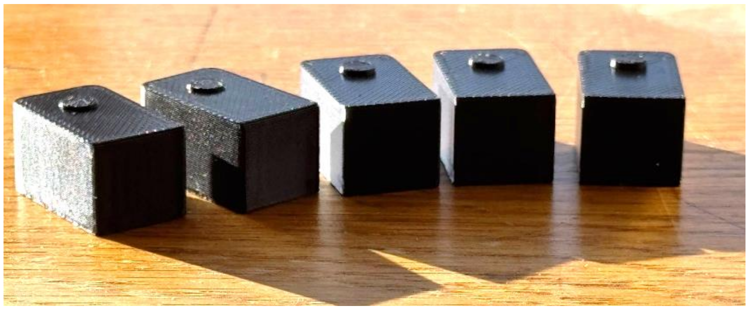
$$= 13.4\ mm - 10.94\ mm - (5.01\ mm - 3.03\ mm) = 0.48\ mm$$

Happily, method 2 verified that the ideal 11 mm spring rest length that I subjectively obtained from method 1, yielded a measured preload 0.48 mm skin displacement that was quite close to the ideal 0.50 mm value that is specified my Dr. Tass.

The above measurements were made under ideal conditions while sitting motionless at a desk. Under less ideal conditions, users may be picking things up or pushing on some external surface. When the tactor is squeezed between a fingertip and some external object, the finger will exert a stronger force against the spring and cause preload displacement to be reduced. When this happens, the perceived vibrational amplitude is increased by about 20%. I don't view this necessarily as bad since Dr. Tass has suggested some modulation of amplitude might actually be helpful in therapy. Note also that the above measurements were taken on an early tactor prototype. After further testing I reduced the button shaft height by 0.3 mm to allow for a bit more room for the compressed spring to keep it from bottoming out when the button is depressed.

Note that my case measurements, H and C, used above do not exactly match the corresponding parameter settings I had programmed into my 3D printer. For example, I had my case height set at 11 mm in my printer, but it actually came out to be 10.94 mm when measured. Therefore, H and C had to be measured on a real tactor because of the slight deviations that occur in the process of printing.

While method 1 and method 2 both provide reliable ways to adjust spring stiffness for individual users, I worried that these methods may not be easy to replicate by novice tactor builders. I then devised a third method based on subjective protrusion feel that is much easier to implement for a novice. In method 3, a set of solid reference tactors are 3D printed with fixed PL button heights of 0.3 mm, 0.4 mm, 0.5 mm, 0.6 mm and 0.7 mm. The test tactors are used as tactile references for users to compare to the feel of a preload displacement being caused by a spring in a tactor that is being tested. The objective in method 3 is to determine an initial spring length that yields a strong localized "zing" when the button is depressed to a height equivalent to the 0.5 mm reference tactor. The additional references are provided to demonstrate to the user what "too high" or "too low" feels like.



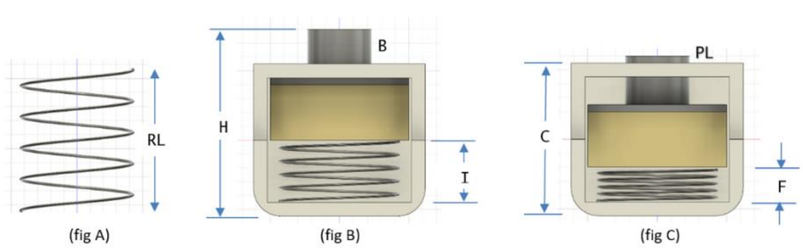
Dummy tactors used to demonstrate the feeling of the ideal preload displacement

Tactor/Finger Mounting

When the tactor is mounted to a fingertip, its entire top surface should be making contact with skin to help block skin vibrations from the button from moving beyond the button area as per Tass specifications. The process of determining the proper tightness by which the tactors are lashed to the fingertip must be performed in concert with the above process to determining spring stiffness. If a tactor is lashed too tight, it will depress the button too far when using a particular spring and result in vibrations that vibrate into finger bones. If you lash the tactor too loosely, the button will be less depressed and result in weaker vibrations. The tactor needs to be tight enough not to slip off the finger during normal use, but not so tight as to cause discomfort. The reference tactors from method 3 above can also be used to help gauge the tightness that achieves proper PL height. Velcro fingertip tighteners are the most reliable way to achieve a precise and reliable lashing that does not stretch out over time. However, I find the Velcro tighteners too annoying because of the loss of dexterity and the fact they tend to grab to fabrics I touch. I alternatively spent much time and energy to find a glove that has the proper finger diameter and elasticity to hold the tactors to my fingers with the correct preloading force. In my quest to find the perfect glove that could be used without Velcro, I tested nearly 20 pairs of gloves from Lowes and Home Depot. I describe my glove choice later in the building section of this grand treatise.

Initial Button Height

The current tactor I use is designed to have a nominal button height, **B** = 2.2 mm. The chamber that houses the spring and LRA ostensively allows for **I** = 4.5 mm of button travel since the LRA thickness is 4.0 mm, the case thickness is 1.0 mm, and the flange thickness is 0.5 mm. Using a button shaft height of 3.2 mm yields **F** = 2.8 mm in the bottom of the chamber to accommodate the compressed spring windings. The 2.8 mm also allows sufficient space to accommodate the 0.03 mm vibration amplitude along with occasional over-compression which occurs when picking up heavy objects, and possible variances occurring in the 3D printing process.



One might think that the nominal 9 mm chamber height could be reduced if B was reduced in order to make a smaller tactor. However, there is a practical concern that requires B to be at least 1 mm. Before the button is depressed, the button flange is forced up against the inside chamber ceiling by the spring. This flange must be pushed clear of inner ceiling of the finger mount in order to facilitate the free vibration of the LRA. Since the vibrational amplitude is only 0.03 mm, the clearance of the button flange from the inner chamber ceiling might not seem to be an issue. However, the top of the spring is angled slightly due to coil pitch, so there is a tendency for the button flange to be slightly canted by the top of the spring. In practice, I found that the flange needs to be pushed in at about 1 mm to safely clear the inside enclosure ceiling and allow free LRA vibration. So, theoretically, B could have been reduced in the tactor design (requiring a slightly stiffer spring). With B = 1.0 mm, the user would only need to depress the button by 0.5 mm to achieve the proper PL. However, when I tested tactor designs with shorter B heights, I found it was too easy for the button to slide off my fingertip when I was performing activities with my hands. With B = 2.2 mm, the buttons reliably remain in contact with my fingers, actively providing therapy, when performing activities that jostle the tactors.

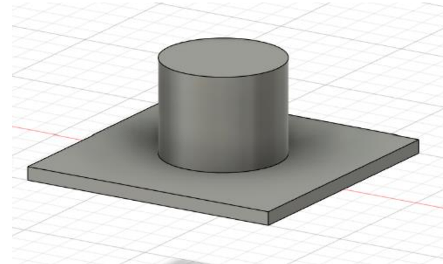
Vibrational Amplitude

The vibrational amplitude of the LRAs in this tactor design is set in the Buzzah software. In all the measurements described previously, I had my amplitude set at 100%. Unfortunately, I could not think of any simple way to actual measure the vibrational amplitude to verify that it matched the 0.03 mm amplitude in the Tass specifications. So, this is a parameter that we must adjust based on user perception. My philosophy when adjusting amplitude is to deliver the highest vibrational amplitude that does not feel like it vibrates into my finger bones. The 100% Buzzah setting yields a stronger perceived fingertip vibration when using the tactor compared to how I used to apply my treatment with an LRA held directly to my fingertip without a tactor. Even though the buzz is stronger when using this tactor, I have left the amplitude at 100% since it does not feel like it is going into my bones when spring tension and mount tightness are adjusted as described above. If I ever felt like I was getting too much vibrational amplitude, I could adjust it lower in the software settings. However, I could not obtain a larger amplitude since I am already at the high limit of my dynamic range without increasing PL.

In summary, skin preload displacement and amplitude are adjusted by trial and error to achieve sufficient zing to clearly sense, but not too much zing as to vibrate areas other than the fingertip. Since there is a variability in the elasticity of different user's skin elasticity, be aware that the setting that works best for my tactors may not work best for you. Velcro tighteners on fingertips help to achieve uninterrupted therapy while doing things, but also result in less dexterity. The table below illustrates measures that can be taken to increase or decrease skin preload displacement and amplitude if you feel your tactor zing needs adjustment.

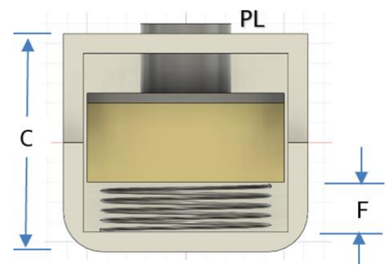
Preload Adjustment	**Action Taken**
To increase preload displacement and increase zing sensation	1. Slightly stretch spring out to increase initial length 2. Make a new spring with using larger diameter wire *(Note: You may also need to change your rod diameter to end up with proper coil diameter if you change wire diameter)*
To decrease preload displacement and decrease zing sensation	1. Make a new spring with closer coils 2. Make a new button with a shorter shaft 3. Make new spring with using 0.011 diameter wire
To adjust buzz amplitude independent of preload displacement	1. Adjust amplitude in Buzzah software settings

Button Diameter



The diameter of the button contact area is not specified by Dr. Tass, however, his tactor manufacturer indicates the 2021 tactors have a contact diameter of 5.1 mm. (See, https://images.hu-production.be/response/460df2ac-7e99-4988-ad8c-cfe50970ad2a.jpg) We tested button diameters of 5.1 mm, 4.6 mm, 3.6 mm, and 2.6 mm with the idea that smaller diameter might give a more point-like vibrational sensation. But smaller diameter buttons also resulted in less perception of the vibrational zing amplitude. So, we quickly eliminated 2.6 mm from consideration. Since button diameters of 5.1 mm, 4.6 mm and 3.6 mm all gave almost identical vibrational sensations, we settled on 5.1 mm used by engineering Acoustics in the link above. The hole we use in the top of the tactor enclosure is currently 5.5 mm to allow free movement of the button shaft, however, we are currently exploring feasibility to increase the size of the enclosure hole to provide a somewhat larger undamped skin area as is found in the Engineering Acoustics tactor.

Friction Between Button Plunger and Inside of Case



The rectangular button flange has edge length of 10 mm which is the same size as the LRA. The inner rectangular chamber is 10.4 mm in length and width, allowing for a 0.2 mm tolerance around all edges to facilitate up/down movement. As the button flange and LRA vibrate, they rub slightly against the walls and create a small amount of friction. Given that the button vibration remains vigorous in spite of this friction, we may ignore any damping effects caused by the friction. The rubbing also produces some vibration of the case during treatment, however, the vibration sensation from button on the fingertip is much greater than that of the case. So, even though the case is vibrating somewhat during treatment from the rubbing on walls, this vibration is very small compared to the button and does not significantly detract from the localized point-like vibration sensation that is required in the Tass vCR treatment. The user can easily gauge the effect of the case vibration during treatment by grounding the tactor to a tabletop during use. When this is done, the case vibration is eliminated and the perceived intensity of the vibration goes up by approximately 20%. The 2021 Tass tactors inherently have less case vibration because the acoustic exciters are so massive. If one wanted to minimize case vibration of this LRA tactor, the mass of the tactor case could be increased by making thicker walls, or somehow affixing small lead weights to the tactors.

Finally, another effect from the rubbing is that the LRA tactors are 2-3 times audibly louder than simply having the LRAs mounted in gloves without a tactor. While the sound is not "loud" by any standard, it is noticeably "louder" than the LRA without a tactor. Perhaps the tactor might be quieter if the walls were made thicker.

3D Printing Filament Type

In all of my early testing, I used PLA to print the print parts. When using PLA, the button hole came out very circular. I switched to ABS for final printing once I had my design criteria settled because I wanted to go with the strongest material. I then noticed that the button hole in the top was coming out with a more oval shape. This does not seem to have had any negative effect on the motion of the button. However, the fit of the endcap became too loose when switching to ABS and I had to reduce my tolerance to zero to get an ideal tight fit. I think PLA is probably strong enough to use for a tactor print. However, be aware if you use PLA to print, you might need to adjust your endcap tolerance so your fit will not be too tight. Also, different printers have varying print characteristics and may require slight adjustments to endcap tolerance.