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Analysis of tactors for wearable simulator feedback: a tactile vest architecture

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ABSTRACT

Current training simulators for police officers and soldiers lack two critical qualities for establishing a compelling sense of immersion within a virtual environment: a strong disincentive to getting shot, and accurate feedback about the bodily location of a shot. This research addresses these issues with hardware architecture for a Tactical Tactile Training Vest (T3V). In this study, we have evaluated the design space of impact “tactors” and present a T3V prototype that can be viscerally felt.

This research focuses on determining the optimal design parameters for creating maximum tactor hitting energy. The energy transferred to the projectile directly relates to the quality of the disincentive. The complete T3V design will include an array of these tactors on front and back of the body to offer accurate spatial feedback.

The impact tactor created and tested for this research is an electromagnetic projectile launcher, similar to a solenoid, but lower profile and higher energy. Our best tactor produced projectile energy of approximately 0.08 Joules with an efficiency at just above 0.1%. Users in an informal pilot study described the feeling as "surprising," "irritating," and "startling," suggesting that this level of force is approaching our target level of disincentive.

Keywords: Tactile vest, tactor, haptic, virtual, bullet, military, impact, pain, training, simulator

1. INTRODUCTION

Training simulators for police officers and soldiers lack a compelling sense of immersion within a virtual environment because of two missing qualities: a physical disincentive to getting shot, and accurate spatial bodily location of a shot. This research presents the hardware architecture of the Tactical Tactile Training Vest (T3V), which has been designed to provide those required qualities of haptic sensation to a user within a virtual or mixed-reality environment. We have evaluated the design space of the necessary impact tactors and describe a T3V prototype that can be viscerally felt and can provide the level of immersion required for virtual combat trainers.

1.1 Virtual military training, environments and training models

The T3V was designed for the MIRAGE, a mixed-reality immersive facility at Iowa State University. While the MIRAGE, a 40’ x 40’ reconfigurable space with high-precision motion tracking, can support a variety of research settings, the T3V was intended for use with the “Veldt,” a particular setting designed for research on military training for dismounted personnel\(^1,2\). Multiple live participants, both friendly and hostile along with their tools or weapons, are tracked in 3-dimensions and are able to interact with virtual or constructive (computer-controlled) entities. The Veldt was designed to be reconfigurable for a multitude of different combat missions, so that in 20 minutes time, the scenario can be changed from a tight Iraqi alley to an open Afghan street scene. The advantage of the Veldt is in the use of artificial intelligence and digitally represented entities (“constructive” and “virtual” respectively.) Normally, in purely live military exercises, role players are dressed up to represent enemy fighters or civilian bystanders. By allowing those characters to be represented digitally, both time and money can be saved in running a training exercise, and scenarios can be highly customized, teaching more than just combat.

Since the Veldt and other types of first-responder training simulators are ultimately trying to teach specific lessons, it is important to define the type of learning model for the exercises. Trainees can either be taught with corrective feedback, or consequential feedback. In terms of military training, corrective feedback would be an After Action Report (AAR), in which a commanding officer explains what happened during an exercise, and identifies what could be done differently.
Consequential feedback is a more exploratory approach to teaching and allows mistakes to happen. For instance in training, a soldier could be allowed to be shot, but must be able to reflect on his or her own mistakes, and must also be allowed the time to re-practice what was learned from the original mistake. “The aspects of immediate feedback plus the consequence of a bit of pain when you make a mistake combine to equal something in force on force training that no other tool can provide. It is one thing to play laser tag and have your buzzer go off. It is another to get smacked by something that gets your attention.”

1.2 Similar systems

Several systems already exist which are capable of providing bodily feedback, but none deliver a powerful impact while being highly mobile, low profile and customizable for spatial feedback. The TN Games’ 3RD Space Vest uses pneumatic tactors, and several other tactile garments use vibration tactors, which are low profile, but lack the quality of sensation needed for this application. The Tactile Gaming Vest from the University of Pennsylvania provides a quality impact, but lacks mobility and a low profile. The Threat-Fire™ from VirTra creates a quality disincentive by shocking the user with electricity, but this belt-clip solution lacks the customization for spatial feedback. Perhaps the least disincentive-based system is the Multiple Integrated Laser Engagement System (MILES) currently in use by the United States Military, which provides only an irritating buzz when the trainee has been shot.

1.3 Similar tactors and design guidelines

The impact tactor described in this research was designed from the ground up for the T3V. The 3RD Space Vest from TN Games and the Tactile Gaming Vest designed by students at the University of Pennsylvania use pneumatic bladders or solenoids as impact tactors, respectively. For a military application however, a new design was needed: a design that was portable, low-profile, and one that delivered an immediate and succinct feedback that a soldier would immediately recognize. The eight air bags (four in front, four in back) in the 3RD Space Vest are low profile and cover a large area of the torso, but there are some drawbacks: the feeling of the disincentive is more akin to a “finger poke” than a jab or a punch, and the air compressor needed to power the vest is loud. Also, it is not readily portable. The housing requirements are also restrictive to this type of tactor driver because of the constant need to draw in air.

The Tactile Gaming Vest at the University of Pennsylvania was created for augmenting movies and theme park type rides. Different types of tactors were explored, including solenoid-based impact tactors, peltier elements designed to induce a burning sensation, and vibrotactile motors. After having tested the 3RD Space Vest, researchers Dr. Katherine Kuchenbecker and Saurabh Palan wanted a better quality of sensation, and didn’t want it to be as loud and cumbersome as the 3RD Space Vest. They also never wanted to induce pain. The researchers at the University of Pennsylvania also distinguished between an “impact,” and a “poke.” If an impact lasts too long, it will feel more like a “finger poke,” so in order to make the sensation feel more like an impact, Kuchenbecker recommended that the impact duration be kept within 100-200 milliseconds.

Avoiding contusions is also important in preserving the livelihood of participants. Excessive energy density of the impact is limited at 13 kilojoules/m² based on the research done by Desmoulin and Anderson, which offers preliminary data for the impact requirement needed to cause bruising in live humans. Since their research was aimed at locating the threshold for where contusions are created, the lower bound of their impact energy density (approximately 13 kilojoules/meter²) is carried over as the T3V impact tactor’s upper bound. The energy and energy density of the impact was tested as described below, but the duration of the actual impact was not tested and is left as an exercise for future work.

The T3V impact tactor was designed to be low-profile and hit hard enough to startle the user, but not to induce pain. Several ideas for impact tactors were explored, such as solenoids, acoustics, bone conducting elements, Gaussian accelerators, expanding artificial muscles or other materials that constrict/expand with current. The solenoid was initially pursued because of its fast response time, while a vibration-based impact tactor (like an eccentric motor, speaker or bone conducting element) was assumed to require a longer actuation time to be noticed by the user, similar to how the Peltier element performed on the TGV, which didn’t seem to be able to portray the urgency that was required of the “you’ve been shot” impact tactor. It is for this reason also that vibrotactile motors were not used to portray the message “you’ve just been hit by a virtual bullet.”
The disincentive of the impact tactor designed in the T3V is what sets it apart from all other training vests, including the high mobility of the entire system. With its low profile design, the T3V can be worn in a high-activity training scenario like the MILES system, but picking up where MILES left off, the T3V is designed to give startling feedback, instead of just annoying. Also unique to this research is the focus on the force of the impact sensation. An impact is defined as a force over a duration of time. The researchers at UPenn defined an appropriate duration to induce this sensation, and this research defines a system capable of varying the force. This physical sensation is a small detail, but is necessary to increase the stress of virtual and mixed reality training simulators to prepare warfighters for actual engagement.

2. METHODS AND PROCEDURES

The approach taken to create the T3V was to identify, design and build individual tactors, test them, and then integrate them into the vest.

While defining the best impact tactor for this application, four different impact tactor prototypes were chosen or created and qualitatively tested. Quantitative testing was performed on the final prototype tactor. The design parameters used to evaluate the prototypes are outlined in Table 1.

Table 1. Qualitative impact tactor requirements

<table>
<thead>
<tr>
<th>Importance</th>
<th>Parameter</th>
<th>Definition</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Quality of Sensation</td>
<td>How startling and attention grabbing is the impact?</td>
<td>Qualitative (Great-Poor)</td>
</tr>
<tr>
<td>Low Profile</td>
<td></td>
<td>How protrusive is the tactor if mounted in the vest?</td>
<td>Profile Clearance (mm)</td>
</tr>
<tr>
<td></td>
<td>Customizability</td>
<td>How readily customizable is the profile or quality of sensation?</td>
<td>Qualitative (Highly-Not at all)</td>
</tr>
<tr>
<td></td>
<td>Repeatability</td>
<td>How repeatable is the impact?</td>
<td>Recovery time (seconds)</td>
</tr>
<tr>
<td>Low</td>
<td>Consumer Off-The-Shelf</td>
<td>Can the tactor and mount be readily purchased?</td>
<td>Yes/No</td>
</tr>
</tbody>
</table>

The quality of the sensation was most important compared to all other parameters because even if there was only tactor on a vest and it can only be repeated every minute, for instance, the message would still be clear that “you’ve just been hit.” Second most important was the physical envelope of the tactor and its ability to be transportable, ruggedized and kept low-profile in order to be unobtrusive during training exercises.

Figure 1. Impact tactor prototype 1: Consumer off the shelf solenoid
2.1 Impact tactor prototype 1

The first prototype explored for the impact tactor was a simple consumer off-the-shelf (COTS) push-style solenoid, directed at the skin of the user. This was modeled after the impact tactor of the U Penn TGV. This tactor had a relatively poor quality of sensation, was not customizable, but had a low profile (28mm, un-energized), as seen in Figure 1. The reason this prototype was discarded was because of the qualitative weakness of the impact.

2.2 Impact tactor prototype 2

The second prototype was based off of the first, in that it also used a COTS solenoid, but was simply much larger. The quality of sensation was qualitatively better than prototype 1, but it had a very large envelope (58mm un-energized) as seen in Figure 2. It was assumed that a vest worn in a high-activity scenario with impact tactors that protruded so far from the mounting surface of the vest would be too obtrusive. Additionally, it was feared that the tactor could be damaged if a trainee bumped up against a wall while working through a scenario, which was enough of a reason to explore other prototypes.

2.3 Impact tactor prototype 3

The third prototype was an exploratory proof of concept based off of a Gaussian accelerator. A Gaussian accelerator is made up of at least three ferric ball bearings and high power magnets as seen in Figure 3 (left). The basic principle of a Gaussian accelerator is that as the ball on the left approaches the magnets, it is accelerated towards the magnet because of the magnetic attraction. As the first ball impacts the magnet, the momentum is transferred through the magnet and intermediate balls and into the ball on the far right. Partially separated from the magnetic field the last ball is able to escape the magnetic field with a high amount of energy that was accumulated by the first ball when it was accelerating toward the magnet. The mathematical principles of this model are left out as this was only a creative proof of concept. The theory of the Gaussian accelerator as an impact tactor was that the trainee would be impacted by the momentum of the last ball.

Figure 2. Impact tactor prototype 2: Consumer off the shelf solenoid

Figure 3. Impact tactor prototype 3: proof of concept gaussian accelerator (left) and chipped magnets (right)
This concept was thrown out because it is unrepeatable without having to manually reset the system. It took considerable force to pry the first ball off of the magnet, and to keep it from accidentally accelerating towards the magnet. After several dozen tests of the prototype, the magnets also started to chip and break apart from the impacts of the ball bearings (Figure 3 (right)). Other concerns arose as to how the system would even be mounted in a contained unit on the vest since the horizontal orientation of the system is critical to its functionality.

2.4 Impact tactor prototype 4

The fourth prototype is a unique approach compared to the previous prototypes and to all of the other impact tactors used on other tactile garments researched and discussed earlier. This tactor was based off of rail gun-type electromagnetic projectile launchers (EMPLs). These devices share the same physical principle as a solenoid, being made up of a coil of wire that, when a high voltage signal is sent through it, induces a magnetic field which accelerates a ferric projectile.

![Image of custom coils for electromagnetic projectile launcher](http://example.com/image1.png)

Figure 4. Impact tactor prototype 4: Custom coils for electromagnetic projectile launcher--small size (left) and large, shielded (right)

One difference between a solenoid and an EMPL however, is the power requirement. A solenoid can operate with a power source of just a few volts, but an EMPL (according to its intended use) needs anywhere from tens of volts to several thousands, applied very quickly—most effectively from a bank of capacitors. The design tradeoff is that the physical form of the electromagnetic projectile launcher can be tailored to the application and if certain design parameters of the coil are changed (i.e. number of turns, gauge of wire used) the power output of the tactor can be fine tuned to deliver a much harder punch. Other factors like voltage input and firing duration were also explored in an effort to increase the actual energy carried by the projectile.

![Image of small EMPL mounted on the wooden vest insert](http://example.com/image2.png)

Figure 5. Small EMPL mounted on the wooden vest insert; projectile is visible inside the EMPL

One major downside of the EMPL is the time it takes to charge the capacitors. With the power source, capacitor bank and boost converter described in the following sections, it took about 25 seconds to charge the capacitor bank up to the
350 volt limit (this limit is discussed in Sec. 4.3). The design was still pursued however, because of the high quality of impact that was delivered to the skin, even through multiple layers of clothing.

The EMPL designed for the T3V went through several different iterations and design tweaks. Several different coils were tested as seen in Figure 4.

The coils for the EMPL were wound tightly with a minor diameter of ~1” and a major diameter of ~2.” Different coils wound with 125 turns of 30 AWG magnet wire, 30 turns of braided 20 AWG insulated wire, and 25 turns of braided 16 AWG insulated wire were created and tested with the same voltage and projectile. The 30 AWG coil was not tested in the EMPL test plan since it produced such a minimal initial resulting acceleration of the projectile, most likely because of the high impedance of the coil. The plastic spools that were purchased with hookup wire used in the making of the electronics were recycled and acted as the housing for the coils. These spools were used because their dimensions were similar to the overall desired tactor size.

In an effort to condense the electromagnetic field during firing, the coil with the 16 AWG wire was also shielded with steel pipe around the perimeter of the coil as can be seen in Figure 4.

The projectiles tested were punched out of 19 Gauge sheet steel to a diameter of 15/16” to freely pass through the 1” opening in the plastic coil housing. The projectile used throughout the EMPL test plan weighed 6.3 grams. The projectiles were roughly the size of a U.S. quarter.

The coil assembly was mounted onto the plywood inserts in the vest as seen in Figure 5. For the preliminary user study, after the EMPL test plans were carried out, a simple projectile return system was created to make the tactor more repeatable. The return system was created by drilling a small hole through the middle of the projectile and by using a cotter pin to attach a one-inch long spring. The other end of the spring was attached to a thin sheet of plastic, which was fixed to the outside of the plywood insert. Unenergized and unsprung, the projectile sat flush with the closest edge of the coil.

2.5 Tactor prototype 4 power supply and control

The impact tactors and vibrotactile motors are controlled from the same microcontroller. The EMPL power supply and control circuitry was designed especially for this application and was made up of a power supply of eight AA batteries feeding into a boost converter circuit which charges a bank of six 390uF, 450 volt capacitors, wired in parallel, up to different target voltages. The firing mechanism between the capacitor bank and the coil is made up of an automotive relay triggered by an NPN transistor. The relay is an electromechanical switch which can handle the high power of the capacitor bank, while being electronically switched with a manageable 12 volts. The transistor itself is triggered by a 5 volt signal from an Arduino Uno microcontroller. The microcontroller is powered by a 5v lithium polymer battery and communicates wirelessly to the host controller, whether it is a computer or another microcontroller via an XBee wireless chip. To prevent attenuation of the wireless signal, the power supply, circuitry, capacitor bank, and microcontroller was housed in a plastic 4” x 6” x 2” enclosure rather than a metal one.

Figure 6. EMPL electronics: boost converter circuitry (left), capacitor bank (upper right) and relay (lower right)
3. IMPACT TACTOR QUANTITATIVE TESTING

Different EMPL tactor coils and conditions were quantitatively tested to determine the overall power carried by the projectile and the efficiency of the coil. Other variables measured were the degradation of the AA battery power supply and the time it took for the capacitor bank to be recharged.

3.1 Explanation of theoretical tactor testing

Ultimately, the test plan is meant to indicate the quality of the sensation delivered by the impact tactor. A quality impact tactor is herein defined as one which delivers a high impulse, where the impulse is defined as the integral of the force with respect to time. To validate this tactor design, only the energy of the projectile was calculated, since measuring the duration of the impact of the projectile with a user’s skin or clothing would be particularly difficult, thus from here on, the validation of the tactor will be in terms of energy of the projectile.

The energy of the projectile cannot be directly measured or calculated like that of the capacitor bank, so instead, the flight time of the projectile was measured as it was shot straight up from the coil. The energy of the projectile was calculated based off of a derivation of two equations, the position of a constant acceleration projectile as a function of time, and the energy of a mechanical system being made up of both potential and kinetic energy.

The approach to solving for the energy of the system is to think of the projectile not as being fired from the ground, following a parabolic displacement curve and falling back to the same position on the ground, but rather as a problem of the projectile falling from its maximum height with no initial velocity. Since the projectile, in reality, is traveling in a parabolic curve, the position is evaluated at time $t_{\text{total}}/2$, since the total time elapsed, $t_{\text{total}}$ represents the duration of time between when the projectile is fired and when it hits the ground.

Since the equation of motion has been constrained to only represent the potential energy of the system, (the energy waiting to be released by the projectile falling from the apex of its trajectory) the potential energy can be calculated by Equation 1, where the proof of this equation is left to the reader.

$$P E_{\text{projectile}} = \frac{1}{2} \times m \times (g \times t)^2$$

Where $m$ is the mass of the particle (in kilograms), $g$ is the force due to gravity (as 9.8 meters/second$^2$) and $t$ is the total elapsed flight time (in seconds) of the projectile. Equation 1 is the equation that was used to calculate the energy of the projectile during the EMPL tests.

The energy contained in a bank of capacitors is far easier to measure than the energy of a projectile. The potential energy stored in a capacitor, $E_{\text{capacitor}}$ (in Joules) is defined as:

$$E_{\text{capacitor}} = \frac{1}{2} \times CV^2$$

Where $C$ is capacitance (in Farads) and $V$ is voltage (in Volts). This equation was also used during the EMPL tests.

Lastly, the efficiency of the projectile launcher can be easily calculated by comparing the energy of the projectile to the energy stored in the capacitors:

$$Efficiency = \frac{P E_{\text{projectile}}}{E_{\text{capacitor}}} \times 100$$

Designed around Equations 1, 2 and 3, a test plan was written to validate the prototypes and discover under which parameters the projectile launcher best performs. In the full test plan, different coil designs and different firing durations were explored at different voltages. The results are shown and discussed in the following sections.
3.2 Tactor test equipment and procedure

The test setup used to perform the EMPL test plan required the use of the EMPL hardware described above, a laptop computer, XBee module and XBee explorer dongle, microphone, multimeter, a small, nonmetallic spacer and a large multimeter, a small, nonmetallic spacer and a large flat surface. The EMPL and coil were placed on the flat surface where there were no obstructions above or around the coil. The coil was placed flat on the surface such that when a positive voltage was applied to the leads, the induced magnetic field would point upwards. Within the coil, the projectile was laid flat on top of the small nonmetallic spacer such that the position of the projectile was directly between the top and the bottom of the coil. The microphone was then positioned near to and oriented at the coil and connected to the computer. The microphone was needed to be able to pick up the sound of the projectile firing and again, hitting the same surface from which it was fired so that the total flight time (and therefore energy) could be measured from the resulting sound file.

To fire the EMPL, the free software X-CTU (10) was used as a serial monitor. When the XBee dongle is plugged into the computer, hitting ENTER in the serial monitor sends the serial code to the wirelessly mated microcontroller. Using the free audio processing software Audacity, the sound of the projectile being fired was captured and reviewed later. Analyzing the sound captured from the firing of the EMPL, it was easy to use the cursor to select the time it took from the beginning of the initial launch to right before the projectile fell back down and hit the flat surface from which it was fired.

4. RESULTS

Quantitatively, the impact tactor’s requirements for functioning properly and efficiently have been thoroughly researched and proven in practice. The electromagnetic projectile launcher (EMPL) repeatedly fired projectiles with, in the best case, about 0.1 Joule of energy and 0.1% coil efficiency.

4.1 Impact tactor test results, experiment 1

In Experiment 1, three different coil designs were tested for overall projectile energy, which directly corresponds to the impulse of the tactor and its efficiency. The efficiency of the coil is important because it shows how much of the voltage is actually applied to accelerating the projectile. It was expected that larger coils would be able to transfer more energy to the projectile. Three trials were carried out at three different target voltages. The actual voltages varied slightly since the system was fired as soon as the voltage in the capacitor bank had recovered. For reference to Experiment 2, all trials in Experiment 1 were carried out with a relay fire duration of 20 milliseconds. The relay fire duration is the duration of time that the relay switch was held closed, which corresponds to the amount of time that the voltage from the capacitors is applied to the coils.

Figure 7 shows the trend of projectile energy vs. capacitor voltage between the small unshielded, large unshielded, and large shielded coils. It was expected that the coil with the more turns and larger gauge wire (the large coil) would produce better results, which is evident in the data collected. The large, shielded coil seems to have produced the best energy results. The average energy of a projectile being fired from the small coil was approximately 0.02 Joules and the average energy resulting from the large coil was 0.06 Joules. The average energy produced with the large shielded coil
was 0.05 Joules, however the data was much more consistent. If the single trial which performed exceptionally well fired from the large, unshielded coil were omitted, the average energy would be 0.04 Joules.

The efficiency of the unshielded coil averaged 0.03% as seen in Figure 8, where the larger coil produced efficiencies varying between almost 0.1% and at the lowest, 0.04%. The overall average efficiency for the large, unshielded coil was approximately 0.06%. Shielding of the large coil also produced an average efficiency of 0.06%.

![Figure 8. Projectile efficiency vs. capacitor bank voltage of small coil (left), large, unshielded coil (middle) and large, shielded coil (right).](image)

It can be assumed, that under ideal conditions, using the exact setup as described in this thesis, the projectile would travel with a maximum of 0.1 Joules, and with a maximum of 0.1% efficiency to the measured power held in the capacitor bank. The energy density was simply obtained by multiplying the energy by the surface area of the projectile. The maximum energy density recorded was approximately 206 joules/m².

### 4.2 Impact tactor test results, experiment 2

Experiment 1 was meant to reveal what coil was best to use, and what voltage was required for that coil to launch the projectile with the most energy. Experiment 2 was designed to test the importance of another variable: the relay fire duration, or how long the capacitor voltage should be applied to the coils. Experiment 2 showed a subtle, but definite trend in the effect of changing the relay firing duration. The best results in Experiment 1 showed that the projectile was launched with an average of 0.06 Joules however at 30ms, the average projectile energy was shown to be slightly above that figure. Similarly, the efficiency also increases slightly, but generally stays around 0.06%.

![Figure 9. Average projectile energy and efficiency vs. relay fire duration](image)

### 4.3 Tactor test discussion

During the testing, not only was the energy of the projectile calculated, but the EMPL circuitry and components were literally tested to their limits. The early versions of the capacitor charger and EMPL were triggered with a simple pushbutton on the outside of the circuit enclosure. Over a half-dozen switches were fused shut and destroyed since the high current levels of the capacitor bank draining overwhelmed the internal components of the switches.
For testing, the pushbutton switch was replaced with the automotive-type relay, which had the benefits of having a much higher power rating, and also being able to be triggered via a computer or microcontroller. During testing, the system failed two different times. While developing this system, the problem of over-charging proved to be very hazardous to the components of the system, where on multiple occasions, the 555 timer, the comparator, the MOSFET, and the 600v diode all broke down and had to be replaced. After this failure during testing, the trials were limited to only 350 volts, so for this system, this is the recommended operating voltage.

The second limit reached was with the relay, which triggered the projectile launcher. This failure was witnessed during the 30 millisecond fire time tests. The relay was fused closed, which was initially witnessed in the lack of residual voltage in the capacitor bank after firing the previous trial. It is assumed that with longer fire times come larger current bursts through the switch, which caused the relay to fail. For this reason, the tests were stopped at 30ms and the recommended fire duration with the current specified components should be limited to 20-25 milliseconds. If the relay component were swapped for one with a higher power rating, it would be possible to push the relay fire duration even longer, but more testing would be necessary to determine the extent to which it can be pushed. Limiting the firing time of the relay does not necessarily limit the impact duration of the projectile.

If the bursts of current do in fact increase with the firing time, then the data collected in Experiment 2 would make sense, with increasing projectile energies with increasing relay fire durations. It is also interesting to note that the average efficiency also increases with increasing fire duration.

The energy density of the EMPL projectile was far less than that shown experimentally to cause bruises in a healthy male. In the research done by Desmoulin and Anderson, the goal was to find 1) What variable correlates with bruising, and 2) the quantity of that variable. The lowest amount of energy density (the variable found to be most closely related with bruising) which caused bruising was approximately 13 kilojoules/m². Assuming the projectile impacts the skin on the entirety of one face, the EMPL currently outputs about 1% of the required energy density needed to cause bruising in a healthy individual. If the projectile impacted a participant’s skin on an edge, the energy density would increase drastically.

Future development of the tactor could explore different shaped projectiles or different techniques of retaining the projectile such that the projectile does not hit the sides of the housing. With this approach it is expected that a more mature EMPL tactor product design could show far greater results. Similarly, if a different relay were used with a higher power rating, more voltage would be able to be sent through the coil, accelerating the projectile even faster.

5. SUMMARY AND DISCUSSION

The prototype tactile vest described herein is meant to provide a stepping stone for future tactile garment and torso-based haptic research, and is not meant to be taken as a finished and polished product. The T3V is a work in progress, but many lessons were learned in researching this subject and creating the prototype tactors and T3V.

5.1 Systems considerations

It is evident that the larger coil outperforms the smaller coil, but more importantly, that the design of the coil itself plays a big role in having a powerful and efficient impact tactor. Endless combinations of coils, coil wire gauge, voltage and firing times could produce a large amount of data which might point to the most efficient tactor design, but that was not the scope of this research. This project and discussion have remained a proof of concept and possible future research platform with which to perform user experiments in mixed or fully virtual reality environments. One important factor which dictates the power of the impact, which was not discussed yet, is the size of the capacitor bank. With larger capacitors and/or more of them to supply more capacitance, an impact tactor system could be designed with a much harder hitting punch.

For future design iterations, a larger capacitor bank is needed, not only for a harder-hitting tactor, but also for a more modular system. If more than one capacitor bank were charging simultaneously, multiple tactors could also be firing simultaneously, adding to the immersiveness of the sensation. Multiple rapid hits on the front of the vest could mean
that you’ve been hit with multiple pieces of shrapnel, or two hits in rapid succession on the front and back could indicate that a virtual bullet has just dealt the participant a devastating through-and-through wound.

With a single impact tactor mounted in the T3V, two wooden chest and back plates, microcontroller and power supply to control them, as seen in Figure 10, the entire vest weighs in at about seven pounds. The circuitry and power supply weighed just two pounds of the total. Expanded to multiple impact tactors and an appropriate capacitor bank and power supply, the vest can be expected to weigh around 10-15 lbs, which is far less than what a typical soldier would carry as a “Fighting Load” which is on average about 62 lbs. The benefit of this design is that a participant using the T3V could also wear actual tactual gear over top of the tactile vest.

5.2 Potential risk

The risk of electric shock is high when dealing with experimental electronics, and the potential for injury is high when dealing with high voltage. Extreme care was always used when charging and discharging capacitors and it is recommended that the circuitry and systems explained herein are approached with caution and used with care. The charging system was not designed to be used in harsh environments and it was not to be used in moist environments or be subject to any kind of moisture to avoid any electric shock. However, for the components designed to be next to the skin, the risk of shock was greatly reduced since the electronics are insulated and shielded.

5.3 Future work

For future iterations of this project it is recommended that the circuitry and capacitor bank be housed in a waterproof and non-conducting enclosure. This approach does present the challenge of allowing adequate cooling of some of the circuitry components. During testing, the MOSFET and high voltage diode became very hot to the touch and if exposed to the skin for an extended amount of time, could possibly cause burns. The prototype included a heat sink attached to the MOSFET, but it is recommended that the diode also be cooled appropriately.

In order to create a system that packed a harder punch, the simplest change would be to increase the capacitance of the capacitor bank. The voltage does not necessarily need to be increased. With this type of change however, a relay rated at a higher power may need to be specified, and the coil design may also need to be changed, with more turns and/or with a larger gauge wire.
To decrease recovery time of the capacitor bank, another simple change to the charging system would be to change the power supply (8 AA batteries) to a high-drain supply like lithium-based or SUBC-type NiCAD batteries.

Also, as with any good system, a feedback loop should be built into the software to alert the master computer to status updates or failures of the T3V.

While these results are preliminary, and further testing will be required to fully optimize the coil and operating conditions, we provide a hardware architecture and systematic testing methodology that will eventually yield a strong solution to the challenge of offering strong shot-feeling feedback in a virtual environment.

REFERENCES


