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Optimizing 3D Printed Tourniquets for Immediate Aid in Ukraine

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Abstract

The outbreak of conflict in Ukraine has been met with a drastic increase in demand for medical devices like the COVID pandemic. Additive manufacturing enables the on-demand onsite manufacturing of medical devices, such as tourniquets, necessary to save lives in emergency situations where delivery isn't an option. Here we show the relative performance of open-source 3D printed GLIA tourniquet components made from ABS and PETG and compare them to a commercially available combat application tourniquet (CAT). Using a variety of mechanical tests, our results demonstrate that tourniquet components printed with PETG are the best alternative to commercially available tourniquets in terms of cost and mechanical properties. We used this work to guide aid efforts for Ukraine through the Open-Source Medical Supply Organization.

Introduction

The objective of this work exceeds the characterization and comparison of tourniquet components. Parallel to optimization we attempt to unravel the worsening state of disaster response status quo fueled by a paradigm of multidimensional inadequacy and explain why additive manufacturing may be effective in redirecting its trajectory. Unfortunately, additive manufacturing has a negative stigma. It has yet to become practical in the minds of many because of glaring inefficiencies. Researchers devoted to the field understand that this technology has value beyond being an interesting way for hobbyists to build mechanically inferior versions of things that already exist. We aim to illustrate the value of additive manufacturing that lies in subtleties showcased in the face of crisis and disaster.

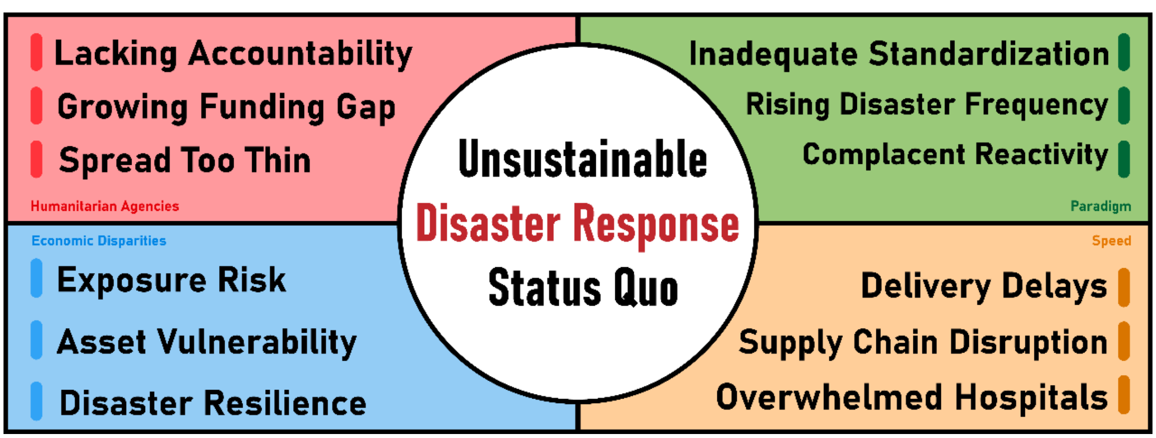

Fig. 1 Miscellaneous contributing factors to the worrying disaster response status quo.

Disasters are happening more often. [1,2,3] This includes both man-made and natural disasters. Man-made disasters arise from a multitude of obscure causes that aren't clearly identifiable compared to natural disasters, leading to disproportionately incomplete, outdated, or unusable data. [4] The global quality of data on man-made disasters (and therefore disaster resilience) can be improved through international standardization but there is no tangible incentive to do so. [4,5] Focusing on a digestible subsection such as industrial disasters help elucidate an alarming general trend. Most industrial incidents involve traditional hazards such as fires or explosions rather than new technology. Instead of collectively improving our ability to mitigate risk to eventually culminate in the eradication of what should be well understood hazards, our priority aimlessly remains on reactivity. Disasters continue to become less deadly because of advancements in medical technology and rapid response, but frequency is still increasing per capita. [1] The current regulatory paradigm is inadequate in ensuring effective management of modern industrial risks. [2] A significant step toward an effective global disaster status quo will have been taken when the frequency of preventable disasters starts consistently decreasing.

If disaster is preventable, it should be prevented. If disaster is unpreventable, its consequences should be smothered through investment in disaster resilience. As technological development progresses and disasters become more intense or frequent, though less people die, an increasing amount are suffering. Investment in disaster reactivity has diminished in its efficacy compared to the pursuit of resilience; there's a limit to how much we can react to at once. The difference is that reactivity frees us from the overcoming of incentive. Without overcoming this natural human tendency, healthy growth will be limited. Unfortunately, increased frequency and inadequate status quo is not unique to the industrial domain.

The total frequency of natural disasters has seen a ten-fold increase since 1960. [1,6] Wars and conflicts are similarly increasing in frequency and duration. [7, 8] Coupled with a growing population and decreased lethality, record numbers of people are affected and displaced by disasters. [1,6] These trends have placed increasing strain on humanitarian agencies, who in 2021 had experienced an average funding shortfall of 40% for five years. [9] This shortfall has since grown to 54% and was growing even before the start of the COVID pandemic. As this funding gap continues to grow, 3% of the world's population (1 in 29 people) are in active need of humanitarian assistance, representing a 250% increase in just seven years. Likewise, by the end of 2020, 82.4 million people were forcibly displaced by conflict and disaster, 42% being children. [10] Need outpaces our ability to help, and this disparity is accelerating.

Even if COVID disappeared along with the funding gap, a lack of accountability may be preventing humanitarian agencies from utilizing their funding properly. [11, 12] In Iraq, a 2019 survey showed that people wanted job opportunities, cash, food, and household items that would help them reduce their dependency, but only 16% of people believe that their opinions were included in aid and service provisions. [9] Likewise in 2020, surveys showed that more than half the people surveyed in Burkina Faso, the Central African Republic, Chad, Nigeria, Somalia and Uganda said that the aid they received did not cover their most important needs. In Chad, only 12% of people surveyed were positive about the aid they received. [9] Instead of listening to the opinions of those directly affected, agencies distribute aid based on what an international committee thinks is needed. Beyond death and suffering, this is an issue of dignity. Without proper consultation and involvement of those directly affected, post-disaster recovery is less successful because there's no opportunity to cultivate permanent resilience and autonomy before the next disaster strikes. [13, 14, 15] This is especially important in poorer countries disproportionately affected by disaster who don't have the resources necessary to develop and maintain effective disaster resilience. [16, 17, 18] An increasing number of countries are completely dependent on foreign aid which is why it's so important we make the switch from a symptom-based to a cause-based mentality with the end goal of permanently increasing preparedness, resilience, and autonomy.

Humanitarian agencies are stretched beyond their means and responsibilities; the status quo is unsustainable, and its trajectory is a tragedy. Change needs to happen before accumulated strain culminates in catastrophic failure of the humanitarian system as we know it today. There are too many lives dependent on this system for it to be permitted to fail. Much of our technological advancements as a species were enabled by catastrophic failure and tragedy; if this remains the driving mechanism to advancement the best case is stagnation, the worst is collapse.

Both during and immediately following a disaster, providing timely medical aid is pivotal. The number of people affected by disasters is increasing each year, meaning more injuries will also be seen. From 2010 to 2020, an annual average of 91,803 people were injured by disaster. [1] In this same time frame, low-income countries had a 64% higher injury rate and a 677% higher mortality rate compared to that of high-income countries. [1, 6, 10] Where resilience fails, the most important factor in preventing injury from becoming death is response time. [19] Approximately 25-50% of injured and dead could be saved if their treatment was provided immediately. [19] Along those same lines, studies of earthquakes in China suggest that unless aid is rendered within 2 to 6 hours, fewer than half the victims will survive. [19] Unfortunately, The COVID pandemic revealed the inadequate governance of our medical supply chain and stockpiles that resulted in worldwide shortages and delivery delays that cost lives. [20] Sometimes delivery can even be impossible to active conflict zones where immediate demand for medical devices is highest. [21, 22] If used in a timely manner, many disaster-related deaths are preventable via rapid interventions such as tourniquets.

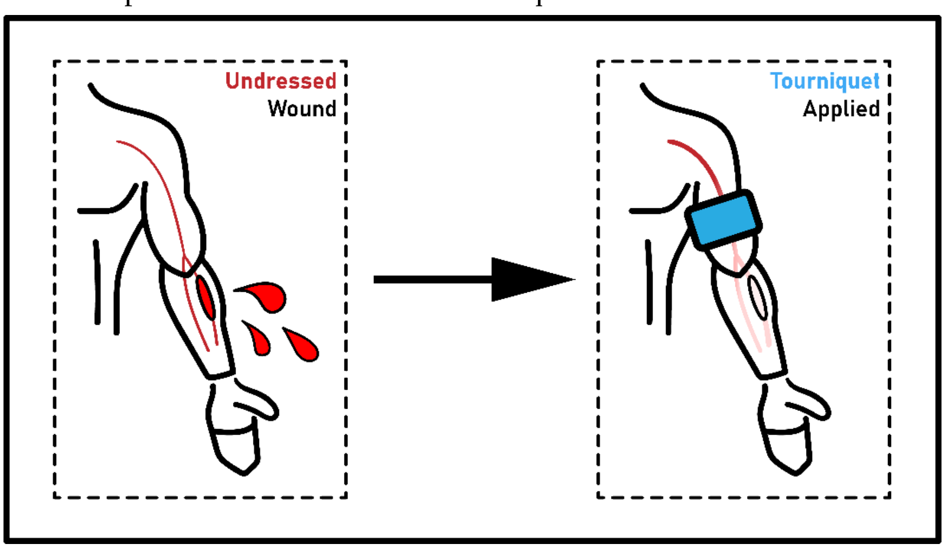

Fig. 2 Proper application of a tourniquet to extremity arrests exsanguination.

Tourniquets are used to apply circumferential pressure to an extremity, occluding blood vessels to arrest life threatening blood loss (exsanguination). Approximately 10% of all battlefield fatalities are the result of extremity exsanguination, greater than half of which are said to be preventable via the usage of medical devices such as tourniquets. [23] Proper utilization of a tourniquet carries many lifesaving benefits, while improper use carries many life-threatening risks. [24-28] Further discussion on the intimacies of tourniquet use is outside of the scope of this paper. The key idea is that a tourniquet can inhibit an otherwise terminal progression of hypovolemic shock in the event of blunt or penetrating trauma common to disasters. The problem, then, is that problems regarding disaster response reduce access to, and proper training for, life saving devices such as tourniquets.

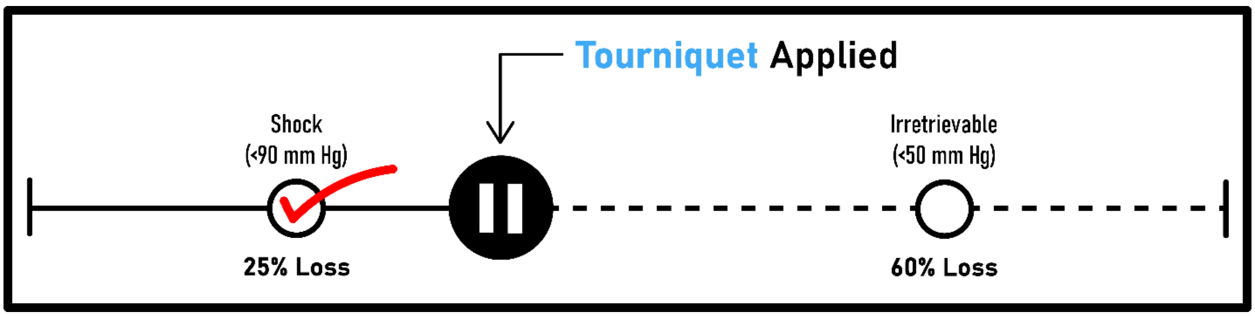

Fig. 3 Proper tourniquet use inhibits progression of hypovolemic shock

The inadequacy of our status quo is multidimensional, seemingly unapproachable like a rampant fire. These circumstances require a wide-reaching solution with the capability to smother multiple problems at once. We believe this solution to be additive manufacturing. Amid increasing disaster frequency additive manufacturing can circumvent delivery problems by producing components onsite and on demand, reduce ill and well-structured costs in developing areas, restore dignity and encourage autonomy by returning some control to those directly affected, alleviate the burden on nearby hospitals by enabling localized small team triage and treatment, and offer effective treatment to a wider range of patients by providing the freedom to design and innovate. Our continued investment into additive manufacturing is a proclamation of our belief that this field is more useful than people have realized, with profound value that only reveals itself in the face of disaster and our inadequate status quo.

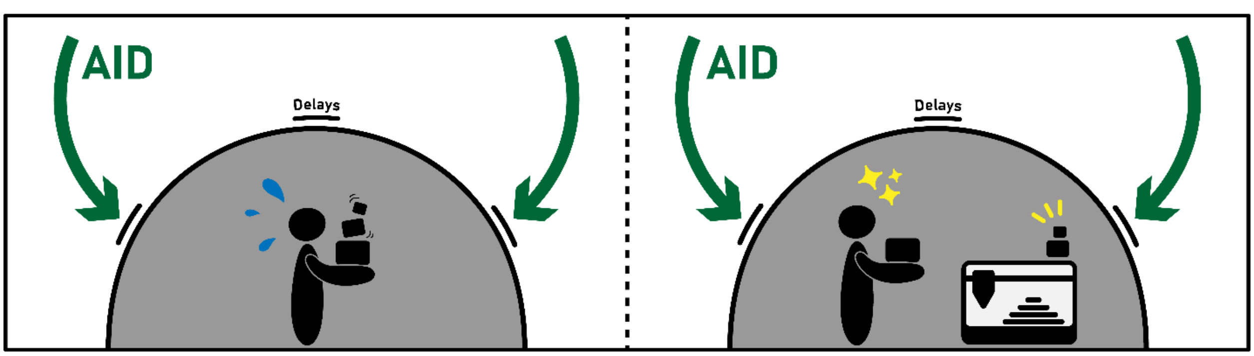

Fig 4. Additive manufacturing circumvents delivery problems, alleviates burden, and restores dignity in the critical period between disaster occurrence and the arrival of substantial aid

Linger until disaster finally touches our ivory towers and all else will be swallowed. Opportunity cannot outlast ignorance and apathy; hope dissipates with these luxuries. Our Great Filter is incentive. Resisting gratifying incentives that lead to collective bad and absence of incentives that lead to collective good.

Results

The foremost purpose of this work was to mechanically characterize Glia's open-source tourniquet components alongside a commercially available injection molded counterpart, the Combat Application Tourniquet (CAT). Tourniquet components printed with ABS have already been deployed to Gaza and Ukraine; the goal of the following tests firstly was to determine if PETG is a worthwhile replacement to ABS and secondly to evaluate how well these 3D printed components mechanically compare to their injection molded counterpart. An Ender-3 Pro was used to print the PETG components, and Fortus 250mc was used to print the ABS components.

The four main components of each tourniquet were the windlass, buckle, backing support, and clip. Each component was mechanically characterized using an Instron load frame, with tests designed to mimic load conditions each component would experience during use. For example, during all uniaxial tension tests, Velcro straps connected the tourniquet component to the load frame gripper to simulate real use. This appeared as a gradual increase in initial stiffness. Force was plotted as a function of displacement for all tests rather than stress as a function of strain because each sample had irregular cross-sectional geometry; an intuitive idea of Young's modulus can still be gained by comparing slopes.

We learned that PETG outperforms ABS mechanically and behaviorally, and while additive manufacturing produces parts inferior to injection molded parts it maintains many advantages over the injection molded component depending on the context of its use. Glia's 3D printed tourniquet components didn't outperform the CAT, but they are far better than nothing, and 'nothing' is far too common in the face of life-threatening disaster and crisis.

Buckle

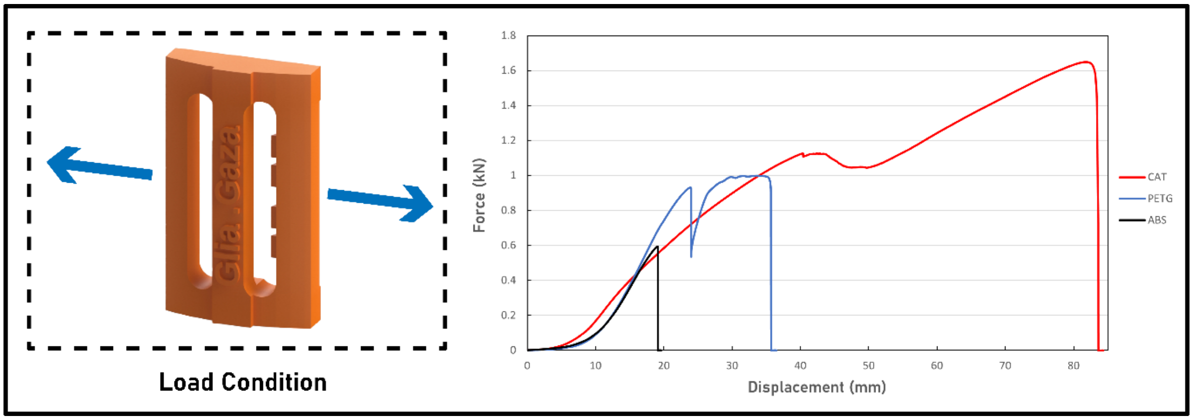

Fig. 5 Results of uniaxial tension test performed on 'buckle' components

When a tourniquet is used, the primary load experienced by the buckle is uniaxial tension as shown in Fig. 5. The buckle supports a Velcro strap wrapped around an extremity in the event of life-threatening blood loss. This failure mode is the limiting factor to performance, which is why it was chosen to evaluate and compare each buckle. The results of this test are shown in the following table where PETG outperforms ABS in mechanical performance while maintaining the benefit of ductile failure. The CAT buckle was less stiff and therefore more pliable with a peak load 65% higher than the PETG buckle.

Table 1 Results of buckle uniaxial tension testing

Material	Slope ($\frac{N}{mm}$)	Peak Load (N)
ABS	63.6	593.7
PETG	77.1	997.8
CAT	32.7	1648.3

Backing Support

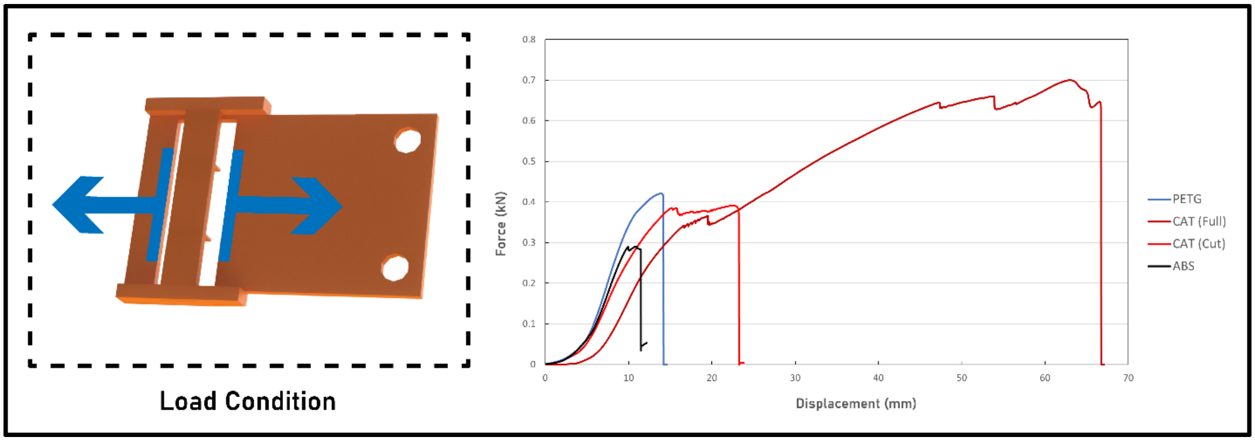

Fig. 6 Results of uniaxial tension test performed on 'backing support' components

Northern American Rescue's CAT is fabricated with the backing support and clip as one continuous component. Fig. 6 shows how this gives the CAT a significant advantage over 3D printed components which, under US Patent #7892253B2 (Item 1.e) and US Patent#7842067 (item 8), must keep the backing support and clip separate. When the CAT backing support is cut out and tested alone, its performance is comparable to a PETG backing support with lower stiffness and peak load but higher pliability. In the event of crisis this patent protection is ethically questionable, but the silver lining is that separating the components allows these tourniquets to better cater to female and pediatric patients with smaller limbs.

Table 2 Results of backing support uniaxial tension testing

Material	Slope ($\frac{N}{mm}$)	Peak Load (N)
ABS	59.7	290.6
PETG	63.2	421.1
CAT (Cut)	45.3	391.8
CAT (Full)	40.7	700.2

Backing Support (Cont.)

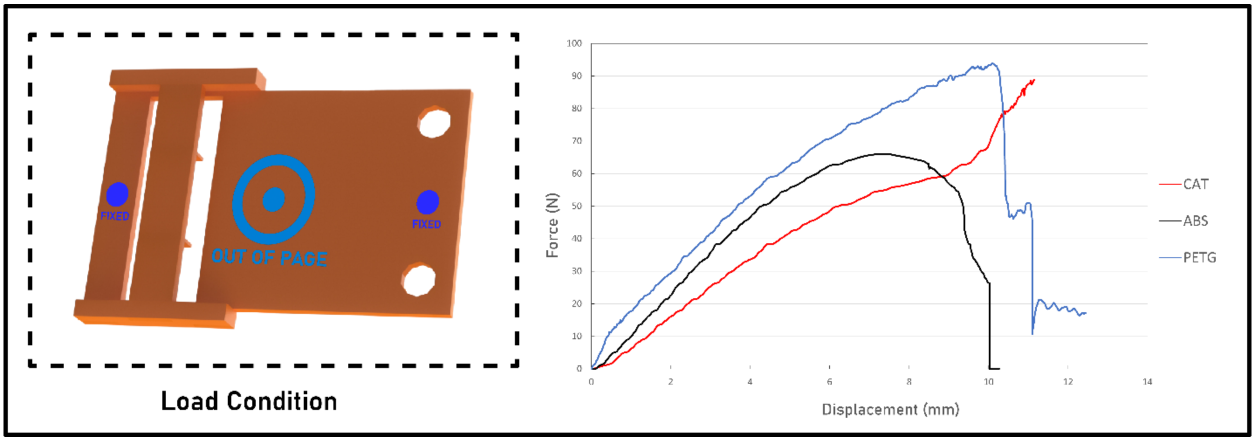

Fig. 7 Results of 3-pt. bend test performed on 'backing support' components

Above 11mm the CAT backing support would repeatedly slip in the 3-pt. bend apparatus reducing data clarity but maintaining an accurate trend. Though omitted in the plot, CAT data increased linearly until reaching a failure load of 129.1N at 16 mm. As shown in Table 3, this is the most mechanically weak tourniquet component. The CAT can compensate for this by connecting the backing support and clip together, but other designers don't have this luxury because of patent protection.

Table 3 Results of backing support 3-pt. bend testing

Material	Slope ($\frac{N}{mm}$)	Peak Load (N)
ABS	13.1	66.1
PETG	12.2	93.9
CAT	9.5	129.1

Clip

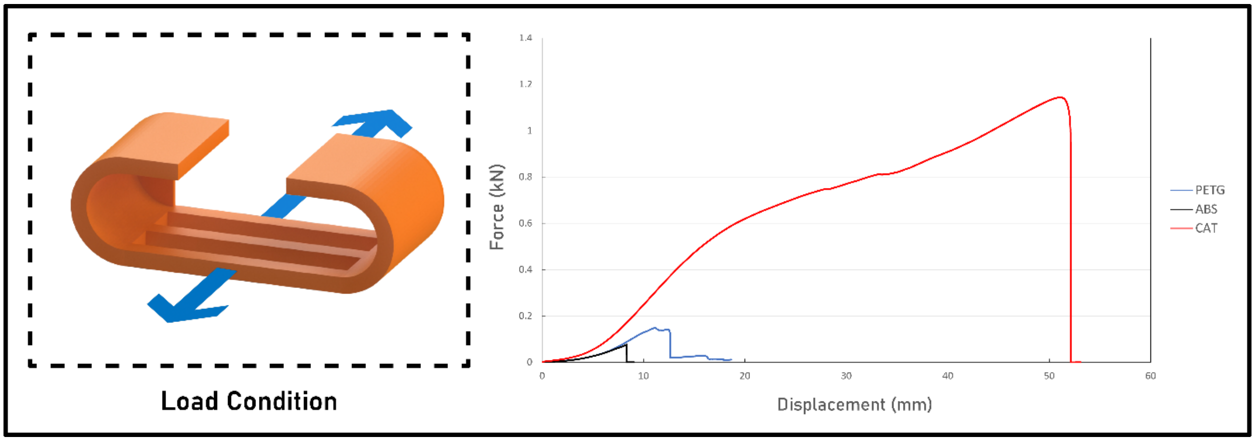

Fig. 8 Results of uniaxial tension test performed on 'clip' components

When a tourniquet is assembled and applied, the clip will experience a uniaxial tension force from the straps, which this test is designed to mimic. The most convenient print orientation for the clip is the worst performing due to anisotropy inherent to the layered filament structure. The load direction in this test was perpendicular to the layers of filament, resulting in markedly worse performance for the printed components. This is the load direction a clip would experience during field use; anisotropy needs to be accounted for when printing. This trend can also be attributed to thin geometry at the corners experiencing high stress concentration, easily alleviated by a bevel on sharp corners.

Table 4 Results of clip uniaxial tension testing

Material	Slope ($\frac{N}{mm}$)	Peak Load (N)
ABS	17.2	76.1
PETG	25.6	148.5
CAT	47.6	1143.4

Windlass

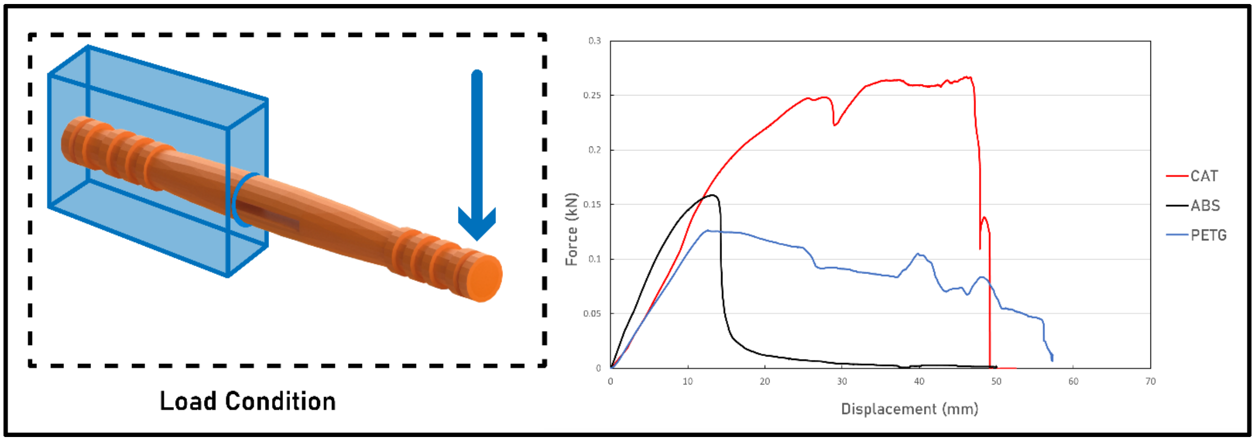

Fig. 9 Results of uniaxial tension test performed on 'windlass' components

This test was designed to mimic a human hand torquing a windlass. When a tourniquet is being tightened around an extremity, human hands on either edge of a windlass exert a moment on the fixed center. This scenario can be approximated by encasing the windlass up to the center and applying a moment-inducing force on a single edge as shown in Fig. 9. This is the only test where PETG did not outperform ABS. This was because delamination occurred at the interface of the bulk interior and the shell of the inner slot. While another windlass could have been printed to test again, this is not what could usually be done in the event of disaster or crisis. Despite having a lower stiffness and peak load, PETG had the benefit of ductile failure as a warning prior to complete failure and prevention of brittle shards entering an open wound. If tunable stiffness were desired per component, additive manufacturing would enable that.

Table 5 Results of clip uniaxial tension testing

Material	Slope ($\frac{N}{mm}$)	Peak Load (N)
ABS	149.5	158.5
PETG	106.1	126.4
CAT	126.3	267.1

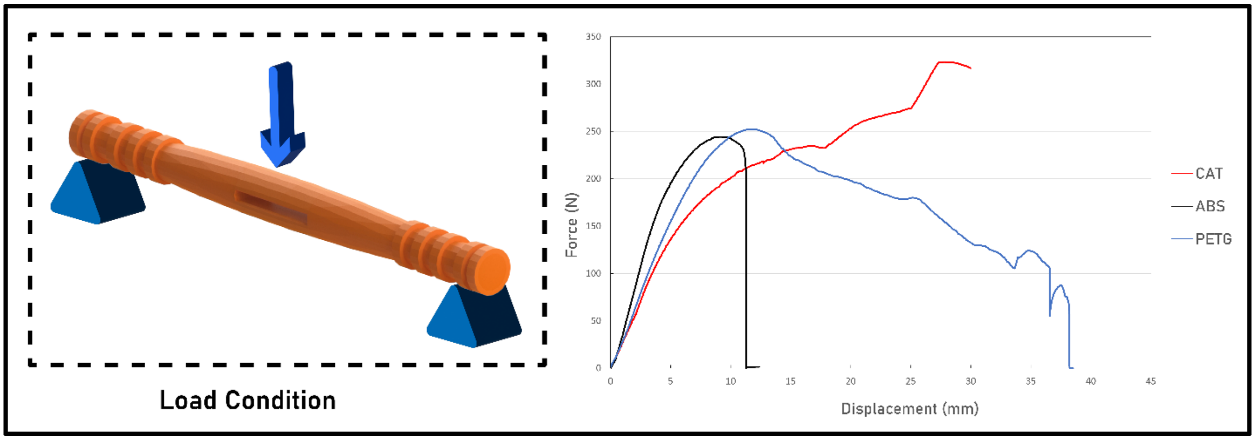

Fig. 10 Results of uniaxial tension test performed on 'windlass' components

Each specimen mechanically behaved as expected during a standard 3-pt. bend test. Data beyond 30mm for the CAT windlass was omitted for the same reason as the CAT backing support during its 3-pt. bend test. Repeated slippage decreased the visual quality of data but maintained an accurate trend; the curve decreased linearly before failing at 50 mm with a force reading of 231 N. The most relevant results are summarized in the following table.

Table 6 Results of clip uniaxial tension testing

Material	Slope ($\frac{N}{mm}$)	Peak Load (N)
ABS	48.1	244.3
PETG	30.8	252.5
CAT	31.37	323.3

Conclusion

This work sought to make three points. Firstly, the status quo for disaster response is unsustainable and pernicious but additive manufacturing can help. In the critical period between disaster occurrence and the arrival of substantial aid, additive manufacturing circumvents delivery problems, alleviates burden, and restores dignity. Secondly, tourniquet components 3D printed with PETG are a better option than ABS. PETG components supported loads up to 68% higher than ABS with the added benefits of flexibility and more ductile failure, important in a tourniquet. Lastly, despite North American Rescue's Combat Application Tourniquet (CAT) being overwhelmingly mechanically superior, 3D printed open-source alternatives can outweigh this difference with value that reveals itself during disaster or crisis. The CAT components always had a higher peak failure load, with one case being 770% higher than the better of the two 3D printed options, illustrating the importance of accounting for print orientation and resulting anisotropy before deployment. While 3D printed tourniquets don't perform as well as their injection molded counterparts, they are better than nothing, and nothing is far too common during crisis and disaster.

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