

Mechanical Assessment of Tissue Properties During Tourniquet Application

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ABSTRACT

Introduction:

Successful tourniquet application increases survival rate of exsanguinating extremity hemorrhage victims. Tactile feedback during tourniquet application training should reflect human tissue properties in order to increase success in the field. This study aims to understand the mechanical properties of a human limb during tourniquet application.

Method:

Six cadaveric extremities—three uppers and three lowers—were tested from three body mass index groups: low (<19) healthy (19–24), and overweight (>24). Each specimen donned with a tourniquet and mounted to a servo-hydraulic testing machine, which enabled controlled tightening of the tourniquet while recording the tourniquet tension force and strap displacement. A thin-film pressure sensor placed between the specimen and the tourniquet recorded contact pressure. Each limb was tested with the tourniquet applied at two different sites resulting in testing at the upper arm, forearm, thigh, and shank.

Results:

The load displacement curves during radial compression were found to be nonlinear overall, with identifiable linear regions. Average contact pressure under the tourniquet strap at 200N and 300N of tension force was 126.3 ($\sigma = 41.2$) mm Hg and 205.3 ($\sigma = 75.3$) mm Hg, respectively. There were no significant differences in tissue stiffness or contact pressure at 300N of tension force between limb (upper vs. lower) or body mass index. At 200N of tension, the upper limb had significantly higher contact pressure than the lower limb ($P = 0.040$). Relative radial compression was significantly different between upper (16.74, $\sigma = 4.16\%$) and lower (10.15, $\sigma = 2.25\%$) extremities at 200N tension ($P = 0.005$).

Conclusions:

Simulation of tissue compression during tourniquet application may be achieved with a material exhibiting elastic properties to mimic the force-displacement behavior seen in cadaveric tissue or with different layers of material. Different trainers for underweight, healthy, and overweight limbs may not be needed. Separate tourniquet training fixtures should be created for the upper and lower extremities.

INTRODUCTION

Tourniquet application in the prehospital setting can save the life of a victim with an exsanguinating extremity hemorrhage by stopping the bleed until advanced surgical treatment can be performed.^{1–3} Survival rates can be increased significantly

with fast successful tourniquet application to prevent hemorrhagic shock.⁴ Since 30% to 50% of trauma-related prehospital deaths occur because of hemorrhage, training is critical to ensure that first responders, medics, medical providers, military members, and civilian community members are proficient in bleeding control, including tourniquet application.^{4–6}

To achieve vessel occlusion, pressure requirements range from 200 to 351 mm Hg. Most commonly, field tourniquet applications and simulations refer to the lower end around 200 mm Hg, with higher pressures in surgery (300–350).⁷ Although technologies exist to detect pressures with pneumatic tourniquet applications in surgery, these are not currently practically applicable in the field. Therefore, the users must use tactile feedback and signs of successful application (bleeding stopped, absence of distal pulse, and reduced capillary refill) to confirm correct and effective tourniquet application.

Many simulation trainers allow users to experience the overall end-point force required to achieve sufficient and appropriate torque on the limb.^{8,9} Low- and high-fidelity trainers can be effective for medical education practice; however, medical educators have noted that even most

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high-fidelity trainers do not simulate skin compression properties for tourniquet application.^{7,10,11} The primary feedback mechanisms in trainers do not employ realistic haptic feedback during the application but rather visual cues such as red light-emitting diodes that turn off (indicating bleeding control), a display informing the user that occlusion is achieved, or a reduced flow of simulated blood. Additionally, the haptic feedback in simulators targets the accuracy of the force required at the end-point of tourniquet tightening versus the haptic feedback associated with the compression resistance of the limb beneath the tourniquet throughout the entire tightening process. In real, prehospital application of tourniquets, the cues that inform the user that bleeding control has been achieved are less obvious. Most indicators, such as reduced bleeding or absent distal pulse, can only be gauged after the complete application of the tourniquet. For a common, windlass-type tourniquet, this would be after both the tourniquet strap and windlass have been tightened. Haptic feedback, on the other hand, is available to the user throughout the tourniquet application and could thus inform the user at an earlier stage whether appropriate torque is being applied, e.g., when tightening the tourniquet strap. Training users to identify the appropriate tightness of the tourniquet could also help address concerns with overtightening and causing injuries or tissue damage.^{12,13}

Tourniquet application training is usually repeated for users, such as that given to military personnel, to develop muscle memory on the task. In order to train users to effectively recognize the tactile feedback they receive when correctly fastening a tourniquet to the appropriate torque, the material properties of the trainer should reflect the properties of human tissue during tourniquet application and thus provide a similar “feel” or haptic feedback for the users. “Buddy training,” or training in pairs or small groups where individuals take turns applying the tourniquet to one another, can allow for training on realistic tissue; however, it includes several drawbacks. First, there are not ideal methods to aid users or trainees in identifying or confirming success (i.e., pressure or precise indication of when the vessel is occluded), which could contribute to either under- or overtightening. Second, it induces pain on the buddy receiving the tourniquet application. Third, training on one buddy may not expose trainees to the variety that exists across limbs with different circumferences or muscle composition. Although some higher fidelity manikin limbs do compress during tourniquet application, it is not clear how accurately they mimic the property of human limbs under compression or how this haptic feedback compares to application on a human. Similarly, the commercially available manikins may not account for the variability in body habitus or composition. When aiming to train muscle memory through haptic feedback, the risk of training the task under wrong conditions could result in user failure in the field.

The aim of this study was therefore to determine the mechanical properties of a human limb during the application of a tourniquet such that an accurate medical simulation of a nonbiological human limb can be created to simulate the

tissue compression and aid in tourniquet application training. The sub-aim was to collect preliminary data for comparison of tissue properties across limbs (upper and lower extremity) and limb location (proximal distal) as well as across body mass index (BMI) categories (underweight, healthy, and overweight).

MATERIALS AND METHODS

Six fresh-frozen cadaveric specimens were obtained from the anatomy department at Mayo Clinic and approved by the Institutional Biospecimens Review Committee (ID 18-001280). Three specimens were upper extremities comprised of the mid-humerus to hand, and three specimens were lower extremities comprised of the mid-femur to foot. Specimens had no evidence of any prior surgical procedure or obvious bone deformity and were thawed to room temperature before testing. Within each three-specimen group of the upper and lower extremities, one specimen was from a donor with a low (<19) BMI, one specimen was from a donor with a healthy BMI (19-24), and one specimen was from an overweight donor (BMI >24). Specimens underwent no surgical dissection or preparation before testing. Each specimen was placed on a servo-hydraulic testing machine (MTS Systems Corporation, Eden Prairie, MN) beneath a custom designed interference plate with a windlass-style tourniquet, the CAT-7 tourniquet (CAT Resources, LLC, Rock Hill, SC), loosely

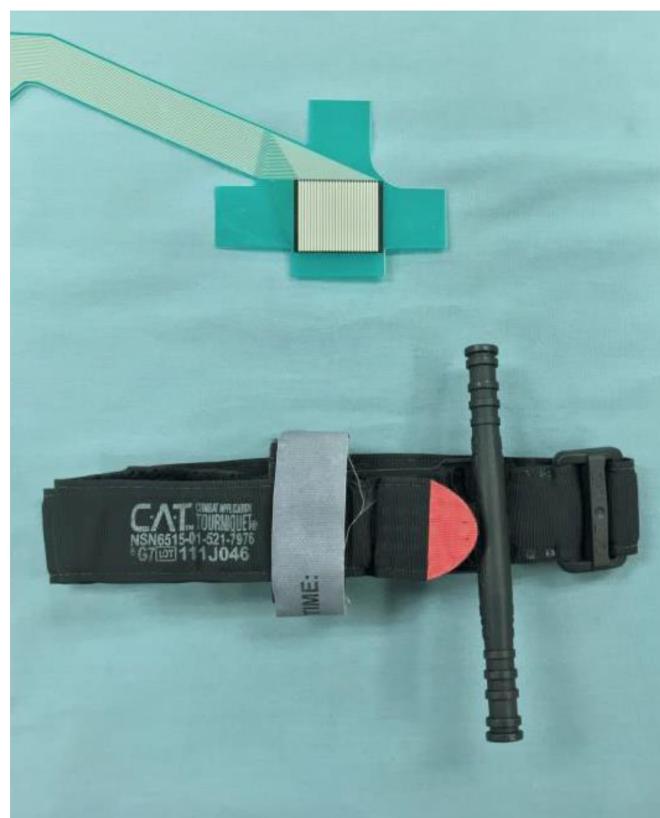


FIGURE 1. Thin film pressure sensor used to measure skin-tourniquet contact pressure (top) and CAT-7 tourniquet (bottom).

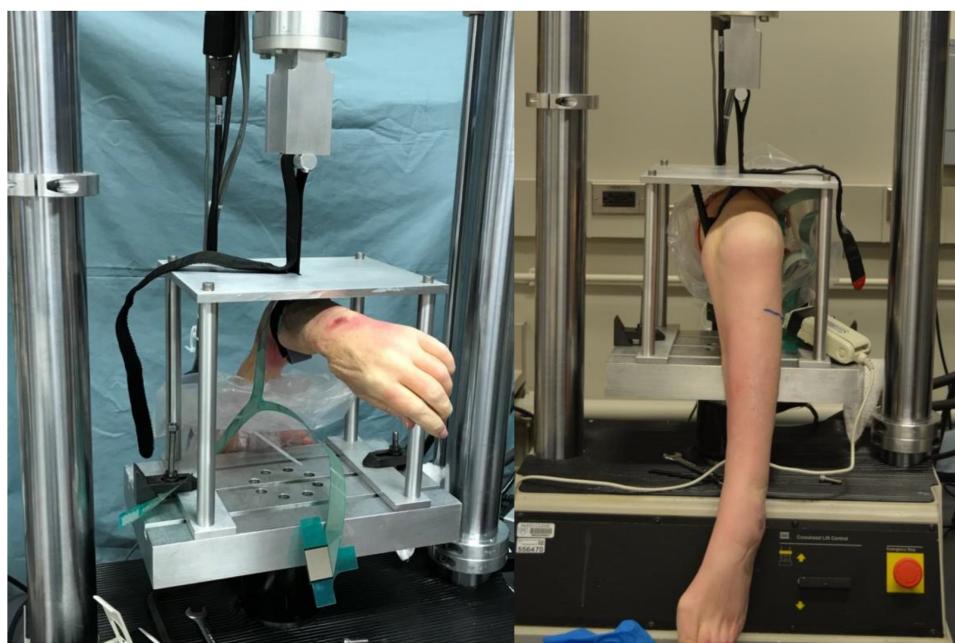


FIGURE 2. Example of upper and lower extremity cadaver limb undergoing tourniquet application test. Free end of tourniquet strap passes interference plate and attached to actuator head. Thin film sensor placed between strap and skin.

wrapped around the desired testing site (Fig. 1). A thin-film pressure sensor (Model 4000, Tekscan Inc., Boston, MA) was used to record the contact pressure applied to the specimen and placed between the specimen's skin and the tourniquet a minimum of 5 cm away from the tourniquet buckle and windlass. The free end of the tourniquet strap passed through a narrow slot in the interference plate and was rigidly fixed to the servo-hydraulic machine's actuator head such that when the strap was pulled by the actuator the strap passed through the interference plate freely while the specimen was held in place, resulting in the consistent tightening of the tourniquet (Fig. 2). Each limb was tested with the tourniquet applied at two different sites. For the upper extremity specimens, these were the 1) upper arm and 2) forearm. For the lower extremity specimens, these were the 1) thigh and 2) shank. Testing sites were located near the elbow and knee joints, shifted proximally and distally just enough to avoid any bony prominence.

Testing consisted of a single tightening of the tourniquet at each specimen-testing site condition. The tourniquet strap was tightened at a rate of 20 mm/min until a load of 300N was reached or the tourniquet hook and loop fixation began to slip. The load and displacement of the strap was recorded at 64 Hz. The contact pressure was recorded at 200N and 300N (when reached before hook and loop slipping) of tourniquet tension.

RESULTS

The load displacement curves of the tourniquet tightening were analyzed and were found to be nonlinear overall, but with identifiable linear regions particularly at the beginning and ending of the loading process (Fig. 3).

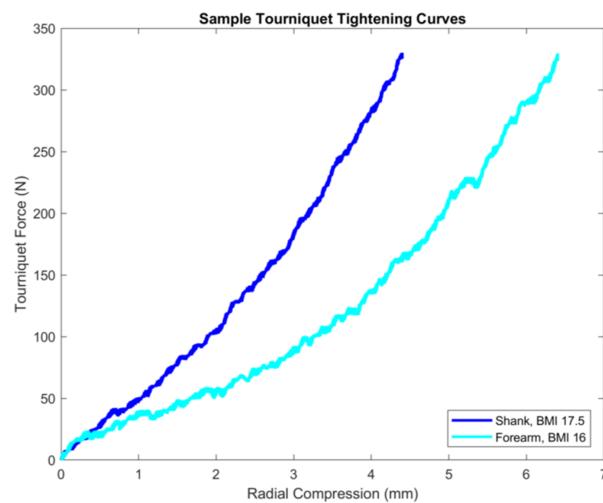


FIGURE 3. Sample load-displacement curves of tourniquet tightening comparing the distal region of the upper and lower limb on underweight body mass index (BMI) specimen.

Therefore, the stiffness of the tissue under tourniquet was computed (via the slope of the load displacement curve) at one low load region and one high load region of the testing with average values of 4.88 ($\sigma = 2.31$) N/mm and 11.42 ($\sigma = 3.53$) N/mm, respectively (Table I). The average contact pressure on skin beneath the tourniquet strap at 200N and 300N of tension force was 126.3 ($\sigma = 41.2$) mm Hg and 205.3 ($\sigma = 75.3$) mm Hg, respectively, assuming even distribution over the limb (Table I). Paired t-tests were run to investigate differences between extremity and BMI. There were no significant

TABLE I. Results of Each Specimen's Stiffness (Stiff), Skin-strap Contact Pressure (Press), Absolute Radial Compression (Comp) and Relative Radial Compression Including Mean and SD

	BMI	Stiff-Low (N/mm)	Stiff-High (N/mm)	Press (mmHg) @ 200N	Press (mmHg) @ 300N	Comp (mm) @ 200N	Comp (%) @ 200N	Comp (mm) @ 300N	Comp (%) @ 300N
Shank	17.5	3.9	14.4	120.0	180.0	3.2	8.5	4.1	11.1
	21.3	4.1	6.9	120.0		6.2	13.3		
	31.5	6.6	13.7	97.5	172.5	4.2	8.6	5.5	11.1
Thigh	17.5	7.4	16.5	97.5	157.5	4.7	11.5	5.8	14.2
	21.3	2.3	5.4	82.5		6.7	11.4		
	31.5	4.4	6.4	90.0	165.0	4.7	7.6	5.1	8.3
Forearm	16.0	3.8	13.8	135.0	277.5	4.9	19.3	6.2	24.2
	21.3	2.8	9.5	187.5		6.2	18.9		
	31.5	3.0	12.1	127.5	232.5	4.5	10.6	5.7	13.3
Upper arm	16.0	4.5	12.8	202.5	345.0	4.5	17.2	5.8	22.1
	21.3	10.5	12.8	172.5		7.1	21.5		
	31.5	5.2	12.8	82.5	112.5	4.3	13.0	5.7	17.2
Mean	23.3	4.9	11.4	126.3	205.3	5.1	13.4	5.5	15.2
SD	6.3	2.3	3.5	41.2	75.3	1.2	4.7	0.6	5.6

Stiff-Low (N/mm), stiffness of specimen at low load; Stiff-High (N/mm), stiffness of specimen at high load; Press (mmHg) @ 200N, contact pressure at 200N of tensile load; Press (mmHg) @ 300N, contact pressure at 300N of tensile load; Comp (mm) @ 200N, absolute radial compression of limb at 200N of tensile load; Comp (%) @ 200N, relative radial compression of limb at 200N of tensile load; Comp (mm) @ 300N, absolute radial compression of limb at 300N of tensile load; Comp (%) @ 300N, relative radial compression of limb at 300N of tensile load.

differences in tissue stiffness or contact pressure at 300N by limb (upper vs. lower) or BMI. However, at 200N the upper limb had significantly higher contact pressure than the lower limb ($P = 0.040$).

The average amount of absolute and relative radial compression of the tissue at 200N of tourniquet force across all limbs and BMIs was 5.11 ($\sigma = 1.17$) mm and 13.45 ($\sigma = 4.69$) %, respectively. When separated by upper and lower extremities, the relative radial compression at 200N was 16.74 ($\sigma = 4.16$) % and 10.15 ($\sigma = 2.25$) %, respectively, a statistically significant difference ($P = 0.005$). However, the absolute radial compression at 200N between the upper and lower extremities was 5.27 ($\sigma = 1.14$) mm and 4.94 ($\sigma = 1.29$) mm, respectively, and not significantly different.

DISCUSSION

The aim of this study was to gain a better understanding of the tissue properties during tourniquet application to inform the design of both tourniquets and tourniquet simulation trainers. By dynamically quantifying the tissue properties during tourniquet application, a target behavior of materials to be used in a tourniquet simulation trainer has been identified. Though the study is limited in that cadaveric specimens contain no blood pressure, the compressive mechanical properties of the tissue remain intact. The two distinct linear regions and other nonlinear regions may indicate a simulation with different layers of material should be assembled. Alternatively, the tissue's compressive properties described by its force-displacement curve may indicate that tissue behaves primarily as an elastic material and a single material with elastic properties may be suitable for a simulation assembly. This differentiation can be clarified with further testing including the

ability of users to differentiate between the tactile feedbacks experienced with each simulated tissue condition.

The use of the contact pressure sensor between the tourniquet and skin allows verification that the forces applied during this in vitro study are comparable to those in vivo. Assuming a standard diastolic blood pressure of 80 mm Hg, these contact pressure values at 200N and 300N of tension equate to approximately 206 mm Hg and 285 mm Hg of overall tourniquet pressure, respectively. These values are in the range of those recommended clinically, 200 to 250 mm Hg.⁷ Research suggests that 200 mm Hg and 250 mm Hg provide complete occlusion of the upper and lower extremities, respectively.⁷ Although the study was limited to only six specimens and thus underpowered, our findings do not show any significant differences in stiffness of the tissue by BMI or between upper and lower limbs. Our findings that the upper extremity is more compressible than the lower extremity supports the predicate finding that total occlusion of the upper extremity is possible with less force than that of the lower. This may indicate that the increased cross-sectional area and total tissue volume in the lower extremity require greater tourniquet force to create occlusion. In other words, there is simply more tissue to compress in the lower extremity and thus more force is needed to compress it to the point of occlusion. Therefore, despite their equivalent tissue mechanical properties, separate tourniquet simulation training fixtures should be created for the upper and lower extremities but may not be necessary by BMI.

Tightening the tourniquet strap to remove all slack during the initial phase of the tourniquet application for the windlass-type tourniquets is what makes the application successful, but research and anecdotal reports indicate that trainees and users in the field often fail to do so.¹⁴⁻¹⁹ Current tourniquet

simulators have achieved ways to measure the pressure or force to indicate success at the end of the tourniquet application.⁸ As discussed in the introduction, however, to train users on muscle memory and the “feel” that indicates successful application, the haptic feedback must be simulated throughout the tourniquet tightening process. Training users on rigid manikins may help teach the tourniquet application tasks but may not provide an opportunity for training the muscle memory. Moreover, training on unrealistic manikins may teach the wrong “feel” and associated muscle memory required for successful application. Additionally, further exploration of the force requirements across limb circumference and body composition may result in further variation on force requirements throughout the entire tightening process. Research by Loenneke and colleagues indicates limb circumference impacts blood flow restriction.²⁰ Although users may never have the opportunity to train on every type of limb, learning what it feels like to tighten the strap to the appropriate torque on models with more accurate material properties may improve their judgment on tightness in the field. Now that objective data indicating the force displacement curve for tissue under tourniquet compression exist, there is a goal for the material properties of a simulation trainer that more closely mimics human tissue. With further validation of the material properties and variability across extremities and body compositions, there will likely be a shift in the training methods for tourniquet simulation from the current end-point force required to the haptics of the tissue compression during the entire process of fastening the tourniquet to the optimal torque.

LIMITATIONS

In this study, the pressure sensor did not measure the pressure around the entire circumference of the limb. The pressure may not be uniform around the entire limb. We expect areas of higher pressure under the plastic plate—especially the edges—on the CAT-7 tourniquet. We avoided pressure measurements in this area for a better representation of pressure on the rest of the tourniquet for this preliminary work. Future work will aim to characterize the distribution of pressure on the surface of the skin because of tourniquet application. Although this small sample size did span across three general BMI categories for this preliminary research, we had limited specimen availability, which resulted in an obese BMI for the category over a BMI of 24, and we could not take body composition into account. The percentage body fat and muscle mass of individuals may more directly impact the tissue properties during compression compared with strictly BMI. For this research, we only used one type of tourniquet. Although we utilized a tourniquet with the windlass system, only the strap was used to measure the tissue compression, the windlass was never engaged. Finally, since the cadaveric specimens contained no blood pressure, the compressive ability to indicate blood vessel occlusion was missing. The

literature indicates change in blood pressure because of blood loss that could impact the required torque to occlude the vessel.^{15,20} Future work is needed to quantify this factor and build it into a simulation trainer. Additionally, an expanded study including a greater number of specimens and tourniquet types could improve the validity of future simulation trainers.

CONCLUSIONS

The results from this study preliminarily indicate simulation of tissue compression during tourniquet application may be achieved with a material exhibiting elastic properties to mimic the force-displacement behavior seen in cadaveric tissue. Alternatively, with two distinct linear regions and other nonlinear regions, a simulation trainer with different layers of material may more accurately simulate tourniquet tissue compression. Initial results indicate different trainers for underweight, healthy, and overweight limbs may not be needed. However, because of greater compression for the upper extremity compared with the lower extremity under the same force, separate tourniquet simulation training fixtures should be created for the upper and lower extremities. Materials that more closely mimic the properties of human tissue under compression may allow for more accurate training of tourniquet application through realistic haptic feedback and should be incorporated into future manikins.

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