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Ultrasound-guided, minimally invasive looped thread fasciotomy for chronic exertional compartment syndrome of the lower leg: A cadaveric feasibility study

Mark Sommerfeldt[a,e,*], Elizabeth Jack[a], Larry Playfair[b], Lalith Satkunam[c], Eldon Loh[d], Brian Rambaransingh[c], Robert Burnham[b,c,f]

[a] Division of Orthopaedic Surgery, Department of Surgery, Faculty of Medicine and Dentistry, University of Alberta, Edmonton, Alberta, Canada
[b] Central Alberta Pain and Rehabilitation Institute, Lacombe, Alberta, Canada
[c] Division of Physical Medicine and Rehabilitation, Faculty of Medicine and Dentistry, University of Alberta, Edmonton, Alberta, Canada
[d] Department of Physical Medicine and Rehabilitation, Schulich School of Medicine and Dentistry, Western University, London, Ontario, Canada
[e] Glen Sather Sports Medicine Clinic, University of Alberta, Edmonton, Alberta, Canada
[f] Vivo Cura Health, Calgary, Alberta, Canada

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ABSTRACT

Background: – Chronic exertional compartment syndrome (CECS) is an exertional pain syndrome that typically affects the lower legs of participants involved in high-intensity running or marching activities. Surgical open fasciotomy is the standard treatment for recalcitrant cases of CECS. Alternative, minimally invasive fasciotomy techniques are emerging which may reduce rates of procedural complications and expedite recovery. The standard fasciotomy procedure for CECS may be improved by looped thread release with additional image guidance. The aim of this study was to describe and evaluate a novel technique of ultrasound-guided, minimally invasive looped thread fasciotomy for release of anterior and lateral compartments of the leg in a cadaveric model. We hypothesized that a fasciotomy of this type would be effective in achieving a target fasciotomy length of 80% of the length of a muscle compartment while avoiding injury to neurovascular structures.

Materials and methods: – We conducted a controlled laboratory study. Two proceduralists performed anterior and lateral compartment fasciotomies on ten lightly embalmed cadaveric legs. A total of twenty compartment releases were completed, using an ultrasound-guided, percutaneous looped cutting thread technique. The specimens were evaluated for length and completeness of fasciotomy, as well as any inadvertent injury to muscle, tendon, or neurovascular structures. Completeness of fasciotomy was compared between the anterior and lateral compartments.

Results: – Eighteen of twenty (90%) fasciotomies were continuous. Fasciotomy length was consistently under target (72% complete). Completeness of lateral compartment release was significantly more likely to be under target compared to anterior compartment release (65% vs. 79%, $p = 0.014$). Sixteen of twenty (80%) fasciotomies incurred no iatrogenic soft tissue injury; no injuries to nerves or vessels were observed.

Discussion –: Ultrasound-guided, minimally invasive looped thread fasciotomy of the anterior and lateral leg compartments is feasible and can be successfully performed in a cadaveric model with low risk to neurovascular structures. However, further investigation is needed to improve completeness of release prior to recommendation for clinical use.

1. Introduction

Chronic exertional compartment syndrome (CECS) is an exertional pain syndrome that typically affects the lower legs of participants involved in high-intensity running or marching activities such as running athletes and soldiers. The pain can be associated with neurologic

* Corresponding author. Division of Orthopaedic Surgery, Department of Surgery, Faculty of Medicine and Dentistry, University of Alberta, Edmonton, Alberta, Canada.

E-mail addresses: marksommerfeldt1@gmail.com (M. Sommerfeldt), ejack1@ualberta.ca (E. Jack), ldplayfair@gmail.com (L. Playfair), LSatkuna@cha.ab.ca (L. Satkunam), eldonloh@gmail.com (E. Loh), brianmd2@gmail.com (B. Rambaransingh), rburnham@capriclinic.ca (R. Burnham).

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symptoms including paresthesiae or weakness. The symptoms of CECS are attributed to activity-related elevation in pressure within one or more muscle compartments of the lower leg [1–4]. Symptoms, which may be present bilaterally, are localized to the affected compartment, with the anterior and lateral compartments being more commonly affected than the deep or superficial posterior compartments of the leg [2,5]. Distinct from acute compartment syndrome, CECS has an onset of symptoms predictably associated with activity and relieved with rest [4]. While the pain may be activity limiting, the affected compartments are typically not at risk of muscle death [6].

The exact pathophysiology of CECS is unclear [7,8]. Muscle hypertrophy, decreased fascial distensibility, obstructed venous outflow, increased interstitial fluid retention, or neurogenic claudication are postulated causes [4,9]. The clinical diagnosis of CECS is typically made after a thorough history, physical examination and, as indicated, investigations to rule out other causes of exertional leg pain such as tibial stress syndrome, stress fracture, tendinopathy, neurogenic claudication from spinal stenosis, or vascular claudication including popliteal artery entrapment, [2,10,11]. The diagnosis is supported by objective measurement of intracompartmental pressures using needle manometry as described by Pedowitz [3]. Most patients are not offered surgical intervention until objective documentation of elevated intracompartmental pressure is demonstrated, which is not the case in acute compartment syndrome [12].

The treatment of CECS begins with conservative measures, including activity modification, physiotherapy, gait re-training, orthotics, and analgesics. Without substantial modification or complete cessation of the aggravating activity, CECS symptoms may persist indefinitely [4,7]. For this reason, CECS has been extensively studied in populations that may be less amenable to limiting their activities, such as athletes and military personnel [1,5,8]. More recently, chemodenervation (botulinum toxin A) has also been used to treat CECS patients [13]. A systematic review of non-operative management of CECS, including massage, gait training, botulinum toxin A and ultrasound-guided fascial fenestration identified that supporting research is scant, of modest quality, and the effect size of treatment is limited. The authors proposed that, of the nonsurgical/non-interventional treatment options, gait modification may be most appropriate for anterior or anterolateral CECS whereas chemodenervation may be most appropriate for deep posterior CECS [14]. If conservative techniques fail, fasciotomy is typically considered [15].

Different fasciotomy techniques have been described, including single and multiple incision, and endoscopic techniques [5,6]. Though reported function and return to activity are favorable after surgical fasciotomy [15,16], recovery results in delays in return to sport/work, and postoperative complications are not uncommon. Post-surgical complications may include hematoma, infection, wound dehiscence, nerve injury, deep vein thrombosis, nerve injury, cosmetically undesirable scarring, and subsequent re-operation [2,4,5,17].

To lower complication rates, improve function and expedite return to activity, authors have been investigating the use of image guidance for fasciotomies. Ultrasound imaging allows for detailed visualization of soft tissue structures and has been utilized to guide open fasciotomy procedures in a case series of patients under spinal anesthesia [15]. To mitigate limitations related to the use of epidural anesthesia and open fasciotomies in outpatient settings, minimally invasive, ultrasound-guided fasciotomy using a meniscotome has been purported as an alternative CECS management technique [18,19]. An ultrasound guided percutaneous needle fenestration of the compartment fascia technique was successfully used on a runner with CESC as an office procedure under local anesthetic and resulted in resumption of running within one week of the procedure and good ongoing relief of the exertional leg pain [20].

Carpal tunnel release is another procedure for which minimally invasive, ultrasound guided procedures are being investigated. Percutaneous thread carpal tunnel release has been described in a cadaveric model [21,22]. It involves the use of sonography to identify the bony pillars of the transverse carpal ligament, the neurovascular structures, and flexor tendons within the carpal tunnel, and to guide the entry and percutaneous passage of a cutting thread superficial and deep to the carpal ligament using hydrodissection. The ligament is then cut by oscillating the two ends of the thread. Clinical trials using this technique in an outpatient setting have demonstrated prompt, significant, subjective and objective improvements in symptoms and function, without serious neurovascular complications [23–25].

These advancements in image guidance and procedural techniques may provide less invasive CECS treatment options and beneficial patient outcomes. The purpose of this study was to investigate the feasibility of ultrasound-guided, minimally invasive looped thread fasciotomy for exertional compartment syndrome of the lower leg.

2. Materials and methods

This study was approved by a local Research Ethics Board (University of Alberta, Pro00077243). Two proceduralists (one Physical Medicine Specialist and one Interventional Radiologist) each performed an equal number of ultrasound-guided anterior and lateral compartment fasciotomies on 10 lightly embalmed cadaveric leg specimens (20 releases total). Ultrasound imaging was utilized to identify and place skin markings over crucial neurovascular structures. These included the common peroneal nerve at the fibular neck, its bifurcation into the deep and superficial branches, and the location in the distal lower leg where the superficial peroneal nerve pierces the crural fascia and becomes superficial to the lateral compartment. While avoiding identified neurovascular structures, the path and proposed extent of the fasciotomies were marked on the overlying skin based on the sonographic appearance of the muscle belly length. Specifically, the distal entry point for the lateral and anterior compartments were ~1 cm proximal to the exit site from the lateral compartment through the crural fascia of the superficial peroneal nerve, and ~1 cm proximal to the inferior myotendonous junction of the tibialis anterior muscle respectively. The exit sites for the lateral and anterior compartments were ~2 cm distal to the common peroneal nerve at the fibular neck (or ~1 cm distal to the bifurcation of the superficial and deep branches if visualized), and ~1 cm distal to myotendonous junction of the proximal tibialis anterior respectively. Generally, the path for the lateral compartment release was just posterior to the midline of the muscle belly. For the anterior compartment, it was 2–3 cm anterior to the fibula.

A custom-made 30 cm-long 18-gauge curved Quincke tip cannula with a 33 cm long stylet (Diros Technology Inc. Markham, Ontario, Canada) was used to place the cutting wire. The cannula, with the stylet removed, was inserted through the skin at the distal skin mark over the compartment to be released. Under ultrasound guidance and using hydrodissection, the cannula was positioned just deep to the superficial fascia. It was advanced proximally while adjusting the direction of the bevel, as required, to ensure the cannula was intimate to the under surface of the fascia and coursed along the predetermined path to the proximal skin mark (Figs. 1 and 2). With the cannula curve angled superficially, the stylet, which was also curved, was advanced through the cannula and exited the skin. The cannula was then advanced further following the stylet and was also delivered through the skin. The stylet was removed and the cutting thread (0.46 mm bead stringing wire, Beadalon, Valley Township, Pennsylvania) was advanced through the cannula. The proximal end of the cutting thread was secured while the operator removed the cannula. Then, the same cannula was reinserted into the same distal portal and advanced just superficial to the fascia following the same path and using the same steering technique. It was delivered through the same proximal skin portal facilitated by the cannula and stylet curvature. The stylet was removed, and the proximal end of the cutting thread was inserted into the end of the cannula and advanced along the cannula shaft to exit the hub. The cannula was then removed from the leg. This resulted in the proximal extent of the

Fig. 1. Ultrasound-guided hydrodissection of the anterior fascia of the lower leg.

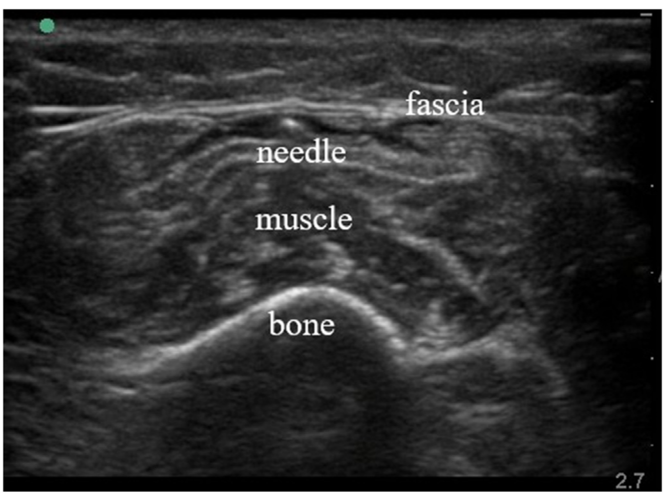

Fig. 2. Ultrasound image depicts the needle placed deep to the lateral compartment fascia in short axis.

compartment fascia being looped with the cutting thread (Fig. 3). Grabbing each end of the cutting thread, the operator oscillated and pulled the thread from proximal to distal until the cutting thread was delivered through the distal portal (Fig. 4). In a few cases, accurate maneuvering of the cannula was challenging enough to require the fasciotomy to be performed in two steps (distal half followed by the proximal half).

While ultrasonographic anatomical landmarks were used to guide the procedure itself, distances relative to palpable bony landmarks were also measured and used to determine target fasciotomy length. Following fasciotomy, dissection of all specimens was performed by a third and fourth investigator (Orthopaedic Surgeon, and Anatomist, respectively) (Fig. 5). The length and completeness of each fasciotomy (actual length versus target length, continuous versus non-continuous), as well as the presence of injury to muscle, tendon or neurovascular structures, were evaluated. Comparison of completeness between the anterior and lateral compartments using an independent samples T test was performed using SPSS version 24 ($p < 0.05$).

3. Theory/calculation

While no gold standard exists in the literature, it was theorized that a

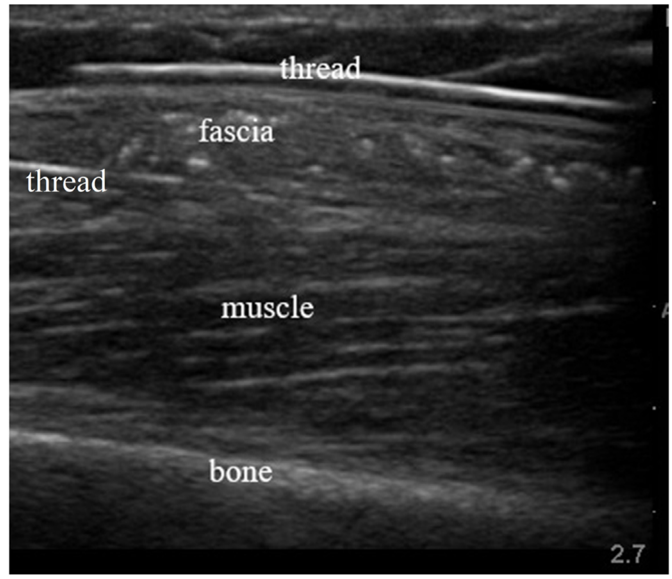

Fig. 3. Ultrasound image that depicts the cutting thread looped around the lateral compartment fascia in long axis.

fasciotomy of this type would be effective in achieving a target fasciotomy length of ≥80% of the length of a muscle compartment while avoiding injury to neurovascular structures. This is based on an estimate that a portion of each compartment is occupied by tendon, which theoretically would not need to be decompressed in the same way as the portion of the compartment occupied by muscle belly.

4. Results

Mean specimen donor age was 86 years (range 69–97), with three female and two male specimens. Mean Body Mass Index (BMI) of four of the specimens was 22.4 kg/m^2 (BMI was not provided with the fifth specimen) (Table 1). Ten anterior and ten lateral compartment fasciotomies were performed on 10 leg specimens. The mean length of all fasciotomies was 17.4 cm; 19.0 cm for anterior compartment fasciotomies, and 15.9 cm for lateral. Compared to the target length determined by bony landmarking, the fasciotomies were all short; on average, 72% of the target fasciotomy length was achieved. Completeness of lateral compartment release (65%) was significantly more likely to be under target than anterior compartment release (79%, $p = 0.014$) (Table 2).

Eighteen of twenty (90%) fasciotomies were continuous. In two instances, fasciotomy of the lateral compartment resulted in a single intact fascial band (2 cm and 0.5 cm, respectively). Sixteen of twenty (80%) fasciotomies were performed without inadvertent injury to surrounding soft tissue structures. There was one instance where fasciotomy of the anterior compartment caused an injury to underlying muscle (3 cm in length), and two instances in which fasciotomy of the lateral compartment caused injury to muscle within the lateral compartment (2 cm) or superficial posterior compartment (3 cm). There was also one partial thickness injury to the peroneus longus tendon during a lateral fasciotomy. There were no injuries to nerves or vessels (Table 3).

5. Discussion

This cadaveric study demonstrated that an ultrasound-guided, minimally invasive looped thread fasciotomy procedure is feasible and is not associated with injury to neurovascular structures. However, it is unclear, based on this experiment alone, whether this novel technique has a role clinically. Additional study is required to further elucidate technical aspects, safety, and utility.

Although minimally invasive procedures may reduce complication

Fig. 4. Oscillating thread fasciotomy.

Fig. 5. Example of completed dissection after fasciotomy.

Table 1
Specimen demographics.

Specimen	Age (y)	Gender	BMI
1	86	M	23.1
2	90	F	22.1
3	90	M	Unknown
4	69	F	29.9
5	88	F	18.8

rates and shorten recovery, these techniques may also lead to greater frequency of incomplete fasciotomies [26]. Incomplete fascial release can result in persistence or recurrence of symptoms, and need for revision [2, 26]. On average, the releases completed in this study were shorter than targeted and hypothesized lengths. It appeared that the lateral compartment fasciotomy lengths were more consistently under-target than anterior compartment fasciotomies. An animal (swine) model investigation has suggested 80–90% fascial release is necessary to adequately reduce intracompartmental pressures [26]. This may suggest a need to set target fasciotomy length based on bony anatomy, rather than ultrasound examination as was done in this study; although, it is uncertain if findings from fasciotomy techniques in animal models will translate to clinically significant reductions of symptoms in humans in vivo. Davies et al. explored adaptations of the ultrasound-guided looped

Table 2
Completeness of fasciotomy procedure.

Specimen (side: R/L)	Compartment	Bony target length (cm)	Fasciotomy length (cm)	Completeness (actual fasciotomy length/bony target length)
1R	Anterior	29.0	23.0	79.3%
1R	Lateral	29.0	15.0	51.7%
1L	Anterior	29.0	23.5	81.0%
1L	Lateral	29.5	21.0	71.2%
2R	Anterior	22.0	17.5	79.5%
2R	Lateral	23.0	14.0	60.9%
2L	Anterior	22.0	20.5	93.2%
2L	Lateral	23.0	21.5	93.5%
3R	Anterior	24.0	19.5	81.3%
3R	Lateral	24.5	16.0	65.3%
3L	Anterior	24.5	19.0	77.6%
3L	Lateral	25.5	14.5	56.9%
4R	Anterior	20.0	19.5	97.5%
4R	Lateral	20.0	12.0	60.0%
4L	Anterior	19.0	14.0	73.7%
4L	Lateral	20.5	14.0	68.3%
5R	Anterior	24.0	16.0	66.7%
5R	Lateral	25.0	18.5	74.0%
5L	Anterior	27.0	17.0	63.0%
5L	Lateral	25.0	12.5	50.0%

Table 3
Complications during fasciotomy procedure.

Specimen (side: R/L)	Compartment	Discontinuous segments	Muscle/tendon injury, compartment
1R	Lateral	1 × 2.0 cm	3 cm muscle, superficial posterior
1L	Lateral		Peroneus longus tendon, lateral
2R	Anterior		3 cm muscle, anterior
2L	Lateral		
3L	Lateral	1 × 0.5 cm	2 cm muscle, lateral

thread release approach of fasciotomy in a single cadaveric specimen and found that long (up to 30 cm) continuous fasciotomy could be safely achieved using a rigid blunt tunneling device [27]. The cutting thread (2-0 silk suture) used in their study was tied to the distal end of the tunneling device that was introduced distally and delivered proximally, deep and superficial to the compartment fascia similar to the looped thread technique. Factors that may make translation of the rigid blunt tunneling device technique into clinical practice challenging include a) the need for open skin incision at the site of introduction and delivery of the tunneling device; b) no capacity to inject local anesthetic through the device to assist with hydrodissection, visualization and anesthesia; and c) potential difficulty securing a cutting wire to the end of the tunneling device. Although the 2-0 silk suture used by Davies et al. could be secured with a knot through the eye of the tip of the tunneling device, the suture broke while cutting approximately 50% of the time. Securing a wire thread to the end of the tunneling device may be more difficult.

Combined lateral and anterior compartment releases have been shown to have a higher failure rate (31%) compared to anterior releases alone (0%) [16]. It is unknown whether lateral compartment anatomy causes a greater technical difficulty in release. Our study demonstrated fewer discontinuous segments as compared to a recent study investigating minimally invasive use of a meniscotome for cadaveric fasciotomy [18]. This may represent the lower likelihood that a long needle is deflected compared to a meniscotome. The clinical significance of discontinuous segments has not been fully elucidated. A recent cadaveric study exploring the safety and feasibility of ultrasound-guided superficial and deep compartment fasciotomy using a V-shaped meniscotome described higher success for the superficial posterior compartment (90% achieved target length; 20% had discontinuous segments) versus the deep posterior compartment (60% achieved target length; 70% had discontinuous segments). No neurovascular injuries were documented [28]. The feasibility of using an ultrasound-guided looped thread technique for fasciotomy of the posterior compartments has not been explored.

Complications in our study were primarily related to muscle or tendon injury, and the lateral compartments were more prone to iatrogenic injuries to these soft tissues. The choice of cutting wire in this study may have been a contributing factor. The cutting wire used in this cadaveric study (bead stringing wire) was selected because it was available and inexpensive. We had successfully used it in the cadaveric feasibility study evaluating thread carpal tunnel release [22]. However, in comparison to the braided surgical cutting wire used in the in vivo study of thread carpal tunnel release [25], the bead stringing wire has a plastic covering around the wire making it is thicker and less malleable. This may have hindered intimate contact of the wire against the compartment fascia. Consideration should be given to using the braided surgical cutting wire for future cadaveric and human thread fasciotomy studies. There was no occurrence of neurovascular injury in any specimen. Our findings represent a lower rate of nerve or vessel injury as compared to a single minimal incision open fasciotomy technique [6], albeit in a cadaveric model. Further, the rate of neurovascular injury in our study (0%) is substantially lower than the rate of nerve-related injuries reported in a recent systematic review [5]. Ultrasound-guided, minimally invasive fasciotomy may reduce neural injuries, sparing altered lower leg sensation and function.

Several limitations and technical factors made this procedure challenging to perform and may hinder its use in an outpatient setting. Although ultrasound is well suited to identify neurovascular structures to be avoided during fasciotomy, the exact start and stop site for a fasciotomy may be difficult to estimate based upon ultrasound imaging of intracompartment muscle alone. Bony landmarks also need to be considered. Additionally, while the sizes of the skin punctures were very small, the path of the needle was relatively long. Performing this extensive procedure comfortably by using local anesthetic during hydrodissection alone may be challenging for some patients. An ultrasound-guided common peroneal nerve block may be necessary to provide additional anesthesia. Ultrasound-guided minimally invasive procedures also have limitations relating to adequate sonographic visualization. Visualization of key structures of the lower leg may be inadequate to perform the thread fasciotomy procedure in the context of obesity or prior surgery in the area. As with surgical open fasciotomy, local or systemic infection, or coagulopathy may also contraindicate thread fasciotomy.

This study focused on the feasibility of a novel surgical technique. The time of each procedure was not formerly evaluated. The experiment, which included fasciotomy and dissection of 10 specimens, was completed in 6 h. The proceduralists in this study noted that manipulation of the long cannula was challenging, suggesting that utilizing a stiffer (i.e. 14 or 16 G) cannula may make the procedure easier.

6. Conclusion

Novel therapeutic options are emerging to effectively treat CECS. Fasciotomy may be indicated in recalcitrant cases and minimally invasive image-guided techniques may translate to lower complication rates and more rapid recovery for patients. Ultrasound-guided looped thread fasciotomy of the anterior and lateral lower leg compartments appears to be feasible and effective in avoiding neurovascular injury in a cadaveric model. Further study is required to improve fasciotomy completeness before recommendation for clinical use.

Disclosures

The authors have no Conflicts of Interest to report.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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