Article

AMERICAN ORTHOPAEDIC FOOT & ANKLE SOCIETY®

Foot & Ankle International®
1–6

DOI: 10.1177/1071100719839944
journals.sagepub.com/home/fai

Comparison of Dorsal Dermal Fascial Fenestrations With Fasciotomy in an Acute Compartment Syndrome Model in the Foot

Reuben Lufrano, MD[1], Matt Nies, MD[1], Beau Ebben, MD[1], Scott Hetzel, MS[2], Robert V. O'Toole, MD[3], and Christopher J. Doro, MD[1]

Abstract

Background: Treatment of compartment syndrome of the foot with fasciotomy remains controversial because of the theoretical risk of infection and soft tissue coverage issues. The purpose of this study was to evaluate the efficacy of compartment decompression with dorsal dermal fascial fenestration compared with fasciotomy in a cadaveric foot compartment syndrome model. We hypothesized that fasciotomies and dorsal dermal fenestrations would provide equivalent compartment decompression.

Methods: Intracompartmental pressure was monitored in the first dorsal interosseous (FDIO), abductor (ABD), and superficial plantar (SP) compartments of 10 fresh frozen cadaveric limbs. A compartment syndrome model was created. Pressure measurements were obtained after dorsal dermal fascial fenestrations and after formal fasciotomies. Primary outcome variables were intracompartmental pressure in the FDIO, ABD, and SP compartments for 4 specific conditions: (1) baseline pressure, (2) pressure after compartment syndrome, (3) pressure after dermal fascial fenestrations, and (4) pressure after fasciotomies.

Results: Fasciotomies decreased compartment pressures to within 10 mm Hg of baseline in all compartments ($P < .001$). Compared with fasciotomies, dorsal dermal fascial fenestrations decreased the average pressure only in the FDIO compartment. Pressure decreases after fasciotomies compared with dorsal dermal fascial fenestrations were significantly greater ($P < .005$).

Conclusion: Fasciotomies were more effective than dorsal dermal fascial fenestrations at decreasing intracompartmental pressure. It seems that dermal fascial fenestrations were unable to provide effective decompression of the ABD and SP compartments of the foot and could provide only partial decompression of the dorsal compartments.

Clinical Relevance: The findings of this study indicate the need for caution in using fenestrations alone to treat acute compartment syndrome of the foot.

Keywords: acute compartment syndrome, dorsal dermal fascial fenestration, fasciotomy

Introduction

Compartment syndrome is an urgent clinical entity characterized by increased pressure in a closed osteofascial space causing decreased tissue perfusion, ischemia, and potentially tissue necrosis. Although most common in the forearm and leg, compartment syndrome of the foot has been increasingly recognized. Since its first description in 1986 by Bonutti and Bell,[1] multiple authors have reported this syndrome occurring in patients with fractures of the calcaneus, Lisfranc injuries, complex metatarsal fractures, and

[1]University of Wisconsin, Department of Orthopedics and Rehabilitation, Madison, WI, USA
[2]University of Wisconsin–Madison, Department of Biostatistics and Medical Informatics, Madison, WI, USA
[3]R Adams Cowley Shock Trauma Center, Department of Orthopaedics, University of Maryland School of Medicine, Baltimore, MD, USA

Corresponding Author:
Christopher J. Doro, MD, University of Wisconsin, Department of Orthopedics and Rehabilitation, 1685 Highland Avenue, 6th Floor, Madison, WI 53705, USA.
Email: doro@ortho.wisc.edu

severe soft tissue injuries and, rarely, after isolated fractures of the leg and ankle.[7,9,11,14,20,22] Overall, the incidence of compartment syndrome after isolated trauma to the foot is estimated to be as high as 2%.[20]

Unlike treatment of compartment syndrome in other body parts, treatment of compartment syndrome of the foot remains controversial. Some authors have argued that untreated compartment syndrome leads to substantial morbidity, including claw toe formation, cavus deformity, sensory deficits, persistent pain, difficulties with footwear, and impaired ambulation.[7,9-11] However, others argue that acute fasciotomy in compartment syndrome of the foot is worse than the outcome of untreated compartment syndrome and theoretically increases the risk of infection and soft tissue coverage issues when treating the underlying fractures.[3] No high-level studies have compared the patient outcomes of these 2 treatment methods.

Recently, several authors advocated for the use of less invasive operative techniques for the management of soft tissue injuries associated with foot trauma.[6,18] It is thought that these techniques would allow for the release of compartment pressure without the soft tissue issues that are associated with traditional foot fasciotomies. Specifically, dorsally based dermal fascial fenestrations are now used at various institutions to treat severe foot trauma.[6,18] To our knowledge, this technique has not been rigorously studied in either a laboratory or clinical setting. Moreover, it is unclear what effect dorsal dermal fascial fenestrations have on the intracompartmental pressure of the foot and whether this technique can be used to treat acute compartment syndrome. The purpose of this study was to evaluate the efficacy of compartment decompression with dorsal dermal fascial fenestrations compared with formal fasciotomies in a cadaveric foot compartment syndrome model. We hypothesized that fasciotomies and dorsal dermal fenestrations would provide equivalent compartment decompression.

Methods

Experimental Setup

Ten fresh frozen cadaveric limbs (7 right, 3 left) were obtained from the Anatomy Gifts Registry. The average age was 73 years. All limbs were thawed at room temperature for 48 hours and amputated below the tibial tuberosity to aid in maneuverability in the laboratory hood. Commercially available plastic zip ties were secured around each leg 5 cm above the tip of the lateral malleolus to prevent fluid egress from the foot to the leg via the posterior neurovascular bundle and the calcaneal compartment, as previously described.[10] Baseline pressure measurements were performed in the first dorsal interosseous (FDIO), abductor (ABD), and superficial plantar (SP) compartments using an intracompartmental pressure monitor (Stryker, Kalamazoo, MI), as would be done clinically. The same 3 compartments were similarly selected for compartment syndrome creation, as described below.

Compartment Syndrome Model

We used a model similar to previously described models.[4,13,19] We attached 3 gravity in-flow intravenous tubing kits to two 1-L bags of sterile 0.9% normal saline solution. An adult-sized blood pressure cuff with attached sphygmomanometer was affixed around each bag of fluid, and the cuffs were inflated to 250 mm Hg. Each line was attached to one of three 1.5-inch 18-gauge needles. The needles were inserted into the FDIO, ABD, and SP compartments in each foot as follows: (1) FDIO compartment via direct palpation of the muscle belly between the first and second metatarsals, (2) ABD compartment at the midportion of the plantar arch just inferior to the first metatarsal, and (3) SP compartment through the plantar aspect of the foot at approximately the same anterior to posterior location as the previously inserted ABD compartment needle (Figure 1). Each compartment was insufflated for 5 minutes before repeating pressure measurements to allow for pressure equilibration. After 5 minutes, the pressure in each compartment was remeasured with the pressure monitor. Pressure measurements were repeated in the same manner after completing both dorsal dermal fascial fenestrations and formal fasciotomies. Compartment pressures were measured immediately after completion of the fasciotomies because they led to rapid visible release of fluid from the foot, obviating the need for a pressure equilibration period.

Baseline pressures in all 3 compartments were less than 10 mm Hg in all cases. Insufflation of normal saline increased average pressures in FDIO, ABD, and SP to 95.4 mm Hg (95% confidence interval [CI], 79.7, 111.1), 87.7 mm Hg (95% CI, 73.7, 101.7), and 96.9 mm Hg (95% CI, 81.8, 112.0), respectively. Average pressure measurements and 95% CI are summarized in Table 1.

Dorsal Dermal Fascial Fenestrations

Five incisions were marked on each of the 10 cadaveric feet before the experiment was begun. Specifically, we marked out four 5-mm incisions in 5-mm increments over the shaft of each metatarsal. The incisions were made with a number 15 blade, and a curved hemostat was used to bluntly dissect to each metatarsal and into the immediately adjacent interosseous muscular compartments. This technique was modeled after that previously described by Dunbar et al[6] (Figure 2). We dissected both laterally into the FDIO compartment and medially into the ABD compartment of the foot via the fenestrations over the first metatarsal. We spread all the way to the deep compartments of the foot through each fenestration

Figure 1. Two views of the experimental setup with intravenous lines and corresponding 18-gauge needles in the abductor compartment (ABD), superficial plantar compartment (SP), and first dorsal interosseous compartment (FDIO) spaces.

Table 1. Average Pressure Measurements (mm Hg) Based on Condition and Compartment Location.

	FDIO	ABD	SP
	Mean (95% CI)		
Baseline	5.3 (0-21.0)	8.8 (0-22.8)	7.6 (0-22.7)
Compartment syndrome model	95.4 (79.7-111.1)	87.7 (73.7-101.7)	96.9 (81.8-112.0)
DDFF	43.2 (27.5-58.9)	70.0 (56.0-84.0)	75.0 (59.9-90.1)
Fasciotomy	11.4 (0-27.1)	8.5 (0-22.5)	10.2 (0-25.3)

Abbreviations: ABD, abductor compartment; CI, confidence interval; DDFF, dorsal dermal fascial fenestration; FDIO, first dorsal interosseous compartment; SP, superficial plantar compartment.

Figure 2. Dorsal dermal fascial fenestrations technique.

site, and pressures were measured before and after dorsal dermal fascial fenestrations, as described above.

Fasciotomies

Fasciotomies were performed on all 10 feet after completion of fenestrations with 2 dorsal and 1 medially based plantar incision, as previously described by Myerson.[15] For the 2 dorsal sites, the incisions from the previous fenestrations over the second and fourth metatarsals were completed with a number 15 blade and the remaining fascia over the interosseous compartments was released sharply. A third curvilinear incision extending from the base of the first metatarsophalangeal joint to the medial tubercle of the calcaneus was used to release the ABD and SP compartments (Figure 3). Compartment pressures were checked again immediately after completion of fasciotomies.

Outcome Variables

Our primary outcome variables were intracompartmental pressure (measured in millimeters of mercury) in the FDIO, ABD, and SP compartments for 4 specific conditions: (1) baseline pressure before creation of the compartment syndrome model, (2) pressure after creation of the compartment syndrome model, (3) pressure after completion of dermal fascial fenestrations, and (4) pressure after fasciotomies.

Statistical Analysis

Repeated measures analysis of variance (RM-ANOVA) was conducted to assess for differences in pressure by condition when averaged across the 3 compartments and separately

Figure 3. Fasciotomy decompressing abductor (ABD) and superficial plantar (SP) compartments.

for each of the 3 compartments. Each RM-ANOVA had condition (4 levels) as a fixed effect and specimen number (10 cadaveric legs numbered 1-10) as a random effect. Two-way post hoc comparisons of pressure between any 2 conditions were conducted with Tukey adjusted *t* tests. All tests were 2-sided and conducted at a .05 significance level. Analysis was conducted using R version 3.1.1 (The R Foundation for Statistical Computing, Vienna, Austria).

Results

All RM-ANOVA models indicated significant differences in pressure among the 4 conditions (all $P < .001$). The primary findings are depicted in Figure 4. Dorsal dermal fascial fenestrations decreased the average pressure in the FDIO compartment from the preintervention compartment syndrome condition to 43.2 mm Hg (95% CI, 27.5, 58.9), which was statistically significant ($P < .001$). The average pressures in the ABD and SP compartments after fenestrations decreased to 70 mm Hg (95% CI, 56.0, 84.0; $P = .11$) and 75 mm Hg (95% CI, 59.9, 90.1; $P = .08$), neither of which was statistically significant. Fasciotomies decreased the average pressures in the FDIO, ABD, and SP compartments to 11.4, 8.5, and 10.2 mm Hg, respectively. No statistically significant differences were shown between baseline and postfasciotomy compartment pressures in any of the 3 compartments (all $P > .8$). When directly compared with dorsal dermal fascial fenestrations, pressure changes after fasciotomy were significantly greater in all 3 compartments studied (all $P < .005$).

Discussion

The purpose of this study was to determine the effect of dorsally based dermal fascial fenestrations on foot compartment pressure in an acute compartment syndrome cadaveric model. Our results show that although dorsal dermal fascial fenestrations were able to reduce pressures from the

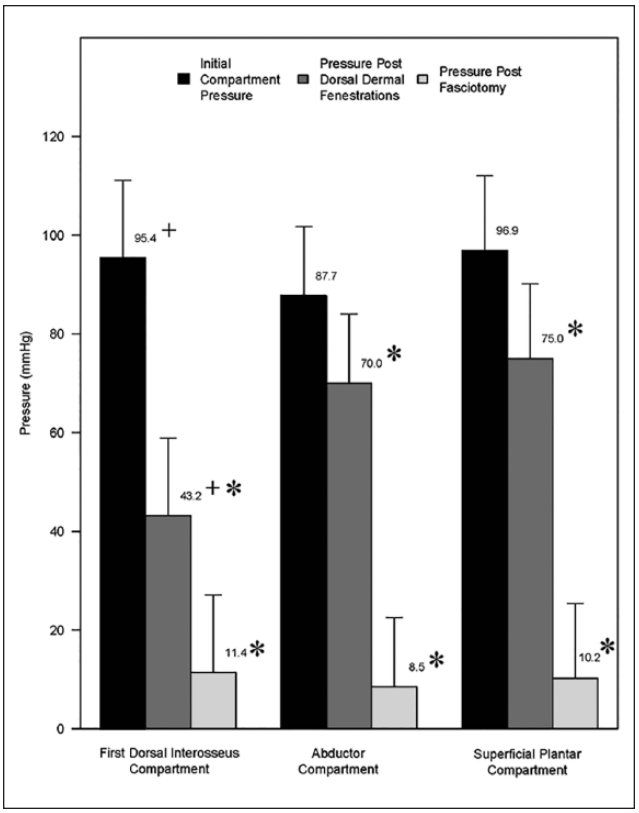

Figure 4. Graphical representation of the average pressure in millimeters of mercury with 95% confidence interval (CI) in the 3 compartments tested: first dorsal interosseous compartment (FDIO), abductor compartment (ABD), and superficial plantar compartment (SP) (listed on the *x* axis). Tukey adjusted *t* test *P* values were calculated between groups. All initial pressure measurements were significantly different ($P \leq .001$) from the final fasciotomy readings. + Only statistically significant measurement ($P < .001$) between initial pressure and pressure after dermal fenestration in the FDIO compartment. * All the compartment pressure changes were significant between the dermal fenestrations and the fasciotomies ($P = .005$, $P < .001$, and $P < .001$, respectively).

compartment syndrome level in the FDIO compartment ($P < .001$) and tended to do so in the SP compartment ($P < .08$), the method was not able to reduce pressures to baseline levels. Average compartment pressure after release with fenestrations, even in their most effective location, was more than 30 mm Hg greater than the baseline compartment pressure and near a delta pressure value of 10 mm Hg, assuming a normal diastolic blood pressure. Traditional fasciotomies, however, reduced pressures from the compartment syndrome value to a statistically significant amount ($P < .001$) in all compartments tested. The pressure change after fasciotomies was also shown to be clinically significant; no statistical variance was shown between postfasciotomy and baseline pressures in each compartment ($P > .20$ compared with baseline).

In contrast to our hypothesis, large differences were observed in the effectiveness of the 2 techniques in lowering pressures in this model, and the differences favored traditional fasciotomies. Although dorsal dermal fascial fenestration might be a valid technique in the management of soft tissue injuries and the promotion of closure of skin defects, our data suggest that it does not provide the same degree of decompression as a formal fasciotomy, particularly in the deeper plantar compartments. However, it is possible that the amount of decompression afforded by fenestrations could decrease pressure enough to avoid acute compartment syndrome.

The length of skin incision of the compartment in question has been shown to significantly influence compartment pressure. Cohen et al[2] reported postfasciotomy pressures in 9 patients with compartment syndrome of the leg after trauma. In that study, pressure after fasciotomy performed with an 8-cm skin incision averaged 25 mm Hg and decreased to an average of 13 mm Hg with isolated lengthening of the skin incision. The results of our study are consistent with those found by Cohen et al and offer an explanation of the decreased efficacy of fenestrations alone. Specifically, fenestrations were not able to decrease pressure to the extent of fasciotomy because of the constraint of a more intact dermal envelope.

To our knowledge, this is the first study to investigate compartment decompression using dermal fascial fenestrations. Dunbar et al[6] previously reported a technique called "dorsal pie crusting," which they noted was a less invasive technique that could reduce infection compared with formal fasciotomy. The authors also reported that the technique could decrease the time required before definitive fixation could be performed because absence of fasciotomies would obviate the need for soft tissue coverage procedures and skin graft maturation. They did warn, however, that patients presenting with symptoms of compartment syndrome who did not experience substantial changes in the appearance of their feet (decreased skin turgor, blanching, mottling, and shininess) after undergoing the technique should be evaluated more thoroughly for undergoing formal fasciotomies. Several years later, Poon et al[18] presented another technique, describing the use of dermal fenestrations at the site of soft tissue swelling and fracture blisters with concomitant negative pressure wound therapy in the treatment of severe soft tissue injuries associated with foot trauma. The authors stated that this technique could prevent progression of severe soft tissue injury to full dermal necrosis or compartment syndrome. They reported 2 clinical cases of patients with jeopardized soft tissues who achieved complete healing of those areas with the technique. No formal cadaveric or human study of the efficacy of these techniques or the outcomes of patients treated with them was provided in either of the reports discussed above.

This study does not answer the question of whether foot compartment syndrome is best treated with any operative decompression. It only addresses the question of which operative technique provides better pressure release. Few data exist on this topic in general, and most series are very small retrospective studies.[9,14,17,22] Deep soft tissue infection and osteomyelitis are cited as potential complications of fasciotomy and as reasons to forgo this procedure in the foot.[3] Ojike et al[17] presented a systematic review of acute compartment syndrome of the foot. Among the 39 cases that the authors reviewed, 65% of patients required split-thickness skin graft, 52% experienced neurological deficits, 39% had residual pain and stiffness, and only 10% returned to work. Despite the high complication rates, the authors stated that complications of operative release are minimal and pale in comparison with complications of delayed treatment, although no comparison delayed treatment group was referenced. A more recent prospective study presented a report of 14 consecutive patients with compartment syndrome who underwent fasciotomy.[9] All patients in that series underwent delayed closure of the fasciotomy incisions, none developed wound infections, and 79% returned to work. This is in contrast to a much larger study assessing plateau fractures and compartment syndrome, reporting infection rates of 25%.[5] Finally, although it did not include a delayed treatment group, the study additionally found that patients with shorter time to fasciotomy correlated with improved foot function, SF-36, and lower pain scores.[9]

Our study additionally did not investigate the compartment anatomy of the foot, which remains controversial. A 4-compartment model was first described by Wood Jones[21] and subsequently corroborated by dye infusion experiments performed by Myerson.[15] That model was challenged by Manoli and Weber[10] in 1990 in a separate dye infusion study of 17 cadaver feet. Based on their results, Manoli and Weber reported the presence of 9 distinct compartments, which differed from previous concepts because of inclusion of separate interosseous, adductor, and deep calcaneal compartments. The model presented by Manoli and Weber is currently the most accepted description of the compartment anatomy of the foot, although other authors[8] have correctly asserted that the methodology of the study by Manoli and Weber offered no technical advance over previous reports. For our study, we chose to measure pressure in the areas we thought to be most clinically relevant and reproducible in a laboratory setting. Measuring all 9 compartments of the foot would be technically difficult and would not represent a pragmatic clinical scenario.

Our study was not without weaknesses. The sample size was relatively small (10 limbs), although we still observed statistically significant findings, indicating adequate power. Another potential weakness was the use of cadaver limbs for the compartment syndrome model, considering cadaveric tissue does not have the same compliance or response to pressure as normal living tissue. Additionally, the compartment syndrome produced in our model was caused by

extracellular fluid administration, whereas most instances of compartment syndrome in vivo result from both intra- and extracellular edema. This potentially decreases the generalizability of our results to human patients but is consistent with previous studies on the subject that have used infusion of isotonic fluid to create a compartment syndrome model.[4,12,16] Our cadaveric model additionally had a benefit over animal studies in that it offered human foot anatomy.

Conclusion

In conclusion, this study found that formal fasciotomies were more effective at decreasing intracompartmental pressure in all compartments compared with dorsal dermal fascial fenestrations. Dermal fascial fenestrations decreased intracompartmental pressure only in the dorsal aspect of the foot and were unable to provide decompression of the plantar compartments despite vigorous blunt dissection to those areas with this technique. Despite a statistically significant decrease in pressure, the clinical usefulness of dermal fascial fenestrations remains suspect because intracompartmental pressure remained markedly elevated compared with both baseline and postfasciotomy levels. Based on the results of our study, we recommend caution in using fenestrations alone to treat acute compartment syndrome of the foot.

Acknowledgments

Dori Kelly, MA, senior editor and writer at the University of Maryland School of Medicine, Department of Orthopaedics, provided professional manuscript editing.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. ICMJE forms for all authors are available online.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

References

1. Bonutti PM, Bell GR. Compartment syndrome of the foot: a case report. *J Bone Joint Surg Am*. 1986;68(9):1449-1451.
2. Cohen MS, Garfin SR, Hargens AR, Mubarak SJ. Acute compartment syndrome: effect of dermotomy on fascial decompression in the leg. *J Bone Joint Surg Br*. 1991;73(2):287-290.
3. Dodd A, Le I. Foot compartment syndrome: diagnosis and management. *J Am Acad Orthop Surg*. 2013;21(11):657-664.
4. Doro CJ, Sitzman TJ, O'Toole RV. Can intramuscular glucose levels diagnose compartment syndrome? *J Trauma Acute Care Surg*. 2014;76(2):474-478.
5. Dubina AG, Paryavi E, Manson TT, Allmon C, O'Toole RV. Surgical site infection in tibial plateau fractures with ipsilateral compartment syndrome. *Injury*. 2017;48(2):495-500.
6. Dunbar RP, Taitsman LA, Sangeorzan BJ, Hansen ST Jr. Technique tip: use of "pie crusting" of the dorsal skin in severe foot injury. *Foot Ankle Int*. 2007;28(7):851-853.
7. Fakhouri AJ, Manoli A II. Acute foot compartment syndromes. *J Orthop Trauma*. 1992;6(2):223-228.
8. Guyton GP, Shearman CM, Saltzman CL. The compartments of the foot revisited: rethinking the validity of cadaver infusion experiments. *J Bone Joint Surg Br*. 2001;83(2):245-249.
9. Han F, Daruwalla ZJ, Shen L, Kumar VP. A prospective study of surgical outcomes and quality of life in severe foot trauma and associated compartment syndrome after fasciotomy. *J Foot Ankle Surg*. 2015;54(3):417-423.
10. Manoli A II, Weber TG. Fasciotomy of the foot: an anatomical study with special reference to release of the calcaneal compartment. *Foot Ankle*. 1990;10(5):267-275.
11. Mittlmeier T, Mächler G, Lob G, Mutschler W, Bauer G, Vogl T. Compartment syndrome of the foot after intraarticular calcaneal fracture. *Clin Orthop Relat Res*. 1991;269:241-248.
12. Moed BR, Thorderson PK. Measurement of intracompartmental pressure: a comparison of the slit catheter, side-ported needle, and simple needle. *J Bone Joint Surg Am*. 1993;75(2):231-235.
13. Morris MR, Harper BL, Hetzel S, et al. The effect of focused instruction on orthopaedic surgery residents' ability to objectively measure intracompartmental pressures in a compartment syndrome model. *J Bone Joint Surg Am*. 2014;96(19):e171.
14. Myerson M, Manoli A. Compartment syndrome of the foot after calcaneal fractures. *Clin Orthop Relat Res*. 1993;290:142-150.
15. Myerson MS. Experimental decompression of the fascial compartments of the foot: the basis for fasciotomy in acute compartment syndromes. *Foot Ankle*. 1988;8(6):308-314.
16. Odland R, Schmidt AH, Hunter B, et al. Use of tissue ultrafiltration for treatment of compartment syndrome: a pilot study using porcine hindlimbs. *J Orthop Trauma*. 2005;19(4):267-275.
17. Ojike NI, Roberts CS, Giannoudis PV. Foot compartment syndrome: a systematic review of the literature. *Acta Orthop Belg*. 2009;75(5):573-580.
18. Poon H, Le Cocq H, Mountain AJ, Sargeant ID. Dermal fenestration with negative pressure wound therapy: a technique for managing soft tissue injuries associated with high-energy complex foot fractures. *J Foot Ankle Surg*. 2016;55(1):161-165.
19. Richter J, Schulze W, Klaas A, Clasbrummel B, Muhr G. Compartment syndrome of the foot: an experimental approach to pressure measurement and release. *Arch Orthop Trauma Surg*. 2008;128(2):199-204.
20. Thakur NA, McDonnell M, Got CJ, Arcand N, Spratt KF, DiGiovanni CW. Injury patterns causing isolated foot compartment syndrome. *J Bone Joint Surg Am*. 2012;94(11):1030-1035.
21. Wood Jones F. *Structure and Function as Seen in the Foot*. Baltimore, MD: Williams &Wilkins; 1944:60-63.
22. Ziv I, Mosheiff R, Zeligowski A, Liebergal M, Lowe J, Segal D. Crush injuries of the foot with compartment syndrome: immediate one-stage management. *Foot Ankle*. 1989;9(4):185-189.