A Modern Surgical Procedure from Ancient Greek Medicine: The earliest documented medical instruction of piezoelectric application in orthopaedic fracture treatment in “On Fractures” (*Περί Αγμών*) of the Hippocratic Corpus, with an addendum on the surgical knots of Heraklas in Oreibasius.

Anagnostis P. Agelarakis

Abstract

Rare in the annals of medical history and surgical practice, palaeopathological findings unearthed from the archaeological site of Paliokastro at Rachoni on Thasos Island, Greece, dating to the Eastern Roman-ProtoByzantine period, shed light on the integration of fundamental methodological procedures for the successful healing of long bone fractures as directed in the approximately one thousand years earlier treatise “On Fractures” of the Hippocratic Corpus. The subject of this article concerns the investigation of aetiological factors that contributed to the preservation and perpetuation of this specific orthopaedic procedure over the span of at least a millennium. Further, based on relatively recent advancements in laboratory medicine, it was possible to trace for the first time the earliest practical application of piezoelectricity in bone healing as elucidated through the Hippocratic methodology. Moreover, an excursus delves into the type of orthopaedic splints recommended in “On Fractures”, and on the surgical knots of Heraklas as described by Oreibasius, providing supplementary insights into ancient medico-surgical techniques in long bone fracture treatment.

Keywords

Hippocratic Corpus, On Fractures, Earliest Piezoelectric Application in Orthopaedics, Bandaging and Splinting in Long Bone Fracture Healing, Heraklas' Surgical Knots, Oreibasius, Hippocratic Code in Eastern Roman-ProtoByzantine Bone Fracture Treatment, Ancient History of Medicine and Surgery

Introduction

A multithemed study of unique anthropological findings recovered from the archaeological site of Paliokastro, at the Rachoni mountainous region in Thasos Island, Greece, (Fig. 1) has provided concrete evidentiary data for the history of medicine on the impressive level of surgical and orthopaedic skills of medical practitioners during the Eastern Roman-ProtoByzantine period[1].

Among the important palaeopathological findings that were to be identified at Paliokastro, there were distinct morpho-anatomic healed fracture manifestations on tibia bone diaphyses that involved both adult male and female individuals[2], reflecting surgical practices implemented in the closed orthopaedic intervention (Fig. 2) which were highly evocative of the methodological instructions for the successful treatment of fracture union, especially of long bones, as had been recommended in the approximately one thousand years older treatise "On Fractures" (*Περί Αγμών*)[3] of the Hippocratic Corpus[4]. A fact which demonstrates that these methods continued to be utilized well beyond classical antiquity.

X-ray images of the tibial diaphyses (Fig. 3)[5] in the investigation of the remodeling and organizational structure of bone at the healed areas of the traumatic nature injuries revealed histo-morphological evidence indicative of the satisfactory reparative state of the osseous tissue, both of the external compact and the internal cancellous bone, illustrating that the bone healing process had taken place quite successfully in terms of the ossification process and bone fusion. In addition, there was a lack of axial rotational deformations among the diaphyseal bone components while their angulation distortion, where relative[6], was well below the current acceptable maximum of 10 degrees. Evidently, in retrospect, it was possible to deduce the successful deterrence of morbidity effects that could have developed in cases of serious wound infection and the dangerous potential of leading to sepsis[7], deep vein

---

[1] Agelarakis, A. P., (2020), Eastern Roman Mounted Archers and Extraordinary Medico-Surgical Interventions at Paliokastro in Thasos Island during the ProtoByzantine Period. The Historical and Medical History Records and the Archaeo-Anthropological Evidence, Archaeopress, Oxford.

[2] Ibid., p.15-16

[3] Hippocrates, Volume III, On Fractures (1999), (Ed.) G. P. Goold, (Transl.) E. T. Withington, Loeb Classical Library, Harvard University Press, Cambridge, Massachusetts, XVIII. 1-28, p. 140-142.

[4] Agelarakis, A. P., (2020), Eastern Roman Mounted Archers and Extraordinary Medico-Surgical Interventions at Paliokastro in Thasos Island during the ProtoByzantine Period. The Historical and Medical History Records and the Archaeo-Anthropological Evidence, Archaeopress, Oxford, p. 17-22.

[5]Ibid., p. 18, Figures 15, and 16.

[6] Ibid., p. 22, and footnotes 67, and 68.

[7] Efron, D., and A. Barbul, (2001), "Wounds in infection and sepsis - role of growth factors and mediators", in (Eds) R. Holzheimer, and J. Mannick, Surgical Treatment: Evidence-Based and Problem-Oriented, Munich, Zuckschwerdt, available from: https://www.ncbi.nlm.nih.gov/books/NBK6957/; Fernanda Mas-Celis, F., Olea-López, J., and Parroquin-Maldonado, J., (2021), "Sepsis in Trauma: A Deadly Complication", *Archives of Medical Research* 52, p. 808–816.

thrombosis[8], fat embolism[9], and/or compartment syndrome[10]. Factors that indicate that this practice often helped prevent the patient's death.

Inquiries that arose from the realization of this evidence, concerning the subject matter of this paper[11], were seeking the possibility of decoding through the medico-historical record and the archaeo-anthropological remains any conceivable practical or beneficial therapeutic reasons that could have contributed towards the millenarian retention during antiquity of the specific orthopaedic methodology. Accordingly, in the investigation of probable causal factors, of particular attention were the repeated instructions in "On Fractures", through both cautionary warnings and directives recommended with authority, for the judicious implementation of a salient procedure which required the recurrence at signature intervals of a distinct, precise and dexterously applied bandaging on the fracture area on schedule with a specified type of splinting[12] during the therapeutic procedure of limb fractures. Further, one of the objectives of this undertaking aimed at the valuation of the ancient orthopaedic practice juxtaposed to intervention approaches and procedures implemented by modern medical science in long bone fractures[13].

Surgical Intervention

As mentioned by Agelarakis in 2020, it is thoroughly described in "On Fractures" that in the case of long bone fractures of the extremities, such as of the arms or the legs[14], the physician (*ιατρός*) attending to the injury, following the initial diagnostic assessments in the conservative treatment, would proceed manually, if man-power would suffice[15], taking all precautions to disentangle and reposition the fractured diaphyseal bone components toward their proper anatomical alignment. Subsequently, initially attending with looser bandaging and by providing proper support for the stabilization of the bone elements[16] the physician would recommend rest and immobilization of the affected limb[17]. Meanwhile, carefully

---

[8] Toker, S., Hask, D., and S. Morgan, (2011), "Deep vein thrombosis prophylaxis in trauma patients", Thrombosis, *Hindawi*, Volume 2011, Article ID 505373.

[9] Shaji, A., Rajpurohit, A., Shankar, J., Saroch, A., Bhatia, M., and Pannu, A., (2022), "Clinical triad of fat embolism syndrome", *QJM: An International Journal of Medicine*, p. 105–106.

[10] Papachristos, I., and Giannoudis, P., (2018), "Acute compartment syndrome of the extremities: an update", *Orthopaedics and Trauma*, 32:4, p. 223-228.

[11] An earlier version of this paper in the Greek language was presented the 29th of September 2023, at the 9th Regional Thasos Conference, Thasos Island, Greece.

[12] Althoff, A.D., Reeves, R.A., (2024), "Splinting" StatPearls Publishing, https://www.ncbi.nlm.nih.gov/books/NBK557673/

[13] Loi, F., Córdova, L.A., Pajarinen, J., Lin, T.H., Yao, Z., and Goodman, S.B., (2016) "Inflammation, fracture and bone repair". Bone, 86, p. 119-30.

[14] Although indicating that variabilities apply in their treatment, Hippocrates, Volume III, On Fractures (1999), (Ed.) G. P. Goold, (Transl.) E. T. Withington, Loeb Classical Library, Harvard University Press, Cambridge, Massachusetts, XIV. 18-21, p. 132-133.

[15] Hippocrates, Volume III, On Fractures (1999), (Ed.) G. P. Goold, (Transl.) E. T. Withington, Loeb Classical Library, Harvard University Press, Cambridge, Massachusetts, XV. 36-39, p. 134-135.

[16] Ibid., XVI. 6-16, p. 136-137.

[17] Ibid., In both cases of traumatic legbone displacements XIV. 29-31, p.132-133, and leg-bone fractures, ibid. XV.

monitoring the patient over the next few days, he was to implement whatever additional orthopaedic alignment adjustments could have been made in the reduction process of the bones. Incidentally, it is noteworthy to underline that a similar intervention process is pursued in modern practice today in closed orthopaedic methodology.

Once assured of the anatomical correctness of the repositioned bone components, the physician after applying wound anointments of pitch cerate at the fracture bone region, first under and then over a thin compress and its adjacent area, would initiate the bandaging starting with greater firmness over the wound at the fracture site[18] using numerous[19], cohesive, wide bandages[20] and then gradually loosening them, but never slackened, the further away he bound from it[21]. While this condition would last for three days, it is clearly explained in "On Fractures" that the purpose of the topical application of pressure on the fracture locus by the bandaging and the orientation of its turns toward the upper part of the limb would prevent the accumulation and stagnation of fluids at the fracture site[22], redirecting them away and toward the sides of the injured limb[23], preventing the formation of an extensive edema[24]. It is further explained that the focal pressure exerted by the properly positioned wide but firm bandages at the site of the fracture would reduce blood flow dynamics[25].

On the third day of this application, the physician would remove the bandages, tending to the patient, and in consultation with the latter's sensation on the degree of pressure exerted in the focal area of the injury, would make adjustments to the application using a new dressing, always using wide bandages, exerting slightly greater firmness specifically on the locus of the fracture site, subsequently loosening once more the fastening pressure of the bandages further away from it. This procedure would continue with applications administered at sequential three-day intervals, with the loosening and relaxation of pressure, subsequently with the repositioning of bandages with a careful application of increased pressure at the fracture site, while at the seventh, ninth or eleventh-day, splints were to be selectively positioned with firm fitting adjustments to the limb with attention to the focal area of the fracture site[26], although with less pressure applied in cases of comminuted fractures[27]. Following repetitive treatments, administered intermittently every three days the binding of dressings would be applied in a looser form, considering that fractured leg bones would fuse in 40 days if properly treated[28].

---

[18] Ibid., XXV. 10-16, p. 150-151.

[19] Ibid., XVI. 8-10, p. 136-137.

[20] Ibid., XXVI. 10-14, p. 154-155.

[21] Ibid., V. 29-34, p. 108-109.

[22] Ibid., XVI. 4-8, p. 136-137

[23] Ibid., V. 23-29, p. 108-109.

[24] Ibid., XVI. 40-50, p. 138-139; and even though referring to upper arm dislocations XLVIII. 1-10, p. 196-197.

[25] As directed for the bandaging of forearm bone fractures, ibid., IV. 23-25, p. 104-105.

[26] Ibid., XVI. 53-58, p. 138-140.

[27] Ibid., XXVI. 51-55, p. 156-157.

[28] Ibid., XVI. 59-60, p. 140-141.

Intervention results

In attempting in retrospect after two and a half millennia to sort out the narrative of this medical advice, its suggestions, and its explanations concerning the warnings provided on the therapeutic approach to be carried out for the proper healing of broken bones in the treatise "On Fractures", it appears that the instructions address foundational components of the Hippocratic methodological procedures in fracture treatment that would have been established by the outcome record of empirical results of medical-orthopaedic interventions. It is reckoned that this would entail the accumulated knowledge of a longstanding medical tradition based on thorough observations and studies regarding the aetiology, type, and variety of fractures in the diverseness of anatomical sites of injuries, the examination criteria, and prognostication[29], the appraisal of intervention approaches through assessments of antedating treatments involved in the healing processes, as well as the cautious organization and management of records derived from careful research that preceded the writing of the specific treatise "On Fractures".

Benchmarked to understandings of modern medical approaches, a retrospective investigation of the outcomes that result in a closed reduction by the application of gentle bandaging in the early stages of fractured limb bone alignment would provide orthopaedical stabilization for the initiation of the healing process, the minimizing of damages to circulation and perfusion of musculoskeletal tissues, yet allowing for a controlled duration of hyperemia in the area of the fractured limb caused by the body's natural response to injury. However, as known through modern laboratory medicine[30] if hyperemia were to persist for an extended period, it could lead to the accumulation of excess fluid and cellular debris in the tissues, hindering the activity of osteoblasts and delaying the reparative bone healing process. Moreover, the increase in blood flow at the trauma site would result in local swelling, redness, and elevated temperature, which are characteristic signs of inflammation. Excessive or prolonged inflammation would be problematic and counterproductive to the bone ossification process[31].

Therefore, having ensured through this ancient closed reduction method the realignment of the fragmented bones and the adequate perfusion of the tissues at the trauma site, the next stage of the Hippocratic methodology dictated that the physician should dress the limb starting with firmer bandaging at the point of fracture and then gradually loosening the compression as its rounds were directed proximally, to primarily dress toward to upper part of the limb, to avoid an influx of blood flow. Essentially, the purpose of the procedure was to prevent two threatening prospects involving the traumatized limb and the survival of the injured individual. Firstly, it was intending to restrict the possibility of the formation of an enlarged edema that would have resulted in the restriction of high tissue perfusion of skeletal muscles causing their necrosis[32] due to the localized increase in volume and prolonged

---

[29] Ibid., XXIX., 1-4, p. 162-163.

[30] Solnica, B., Dabrowska, M., and Sypniewska, G., (2010), "Laboratory Medicine as a Profession and Clinical Science - How to Perform Both of them well?", *The Journal of the International Federation of Clinical Chemistry and Laboratory Medicine*, 21:3, p. 53-5.

[31] Loi, F., Córdova, L.A., Pajarinen, J., Lin, T.H., Yao, Z., and Goodman, S.B., (2016) "Inflammation, fracture and bone repair". *Bone*, 86, p. 119-30.

[32] Warnings on the muti-causal effects of necrosis in limb trauma, including those involved with improper medical treatment, that end up in the death of the patient are offered in Hippocrates, Volume III, On Fractures (1999), (Ed.) G. P. Goold, (Transl.) E. T. Withington, Loeb Classical Library, Harvard University Press, Cambridge, Massachusetts, X., 26-39, p. 122-125.

intracompartmental pressure on the fasciae of the anatomical muscle compartment(s)[33] in the area of the fracture and of their insufficient blood supply.

The inability in antiquity to evaluate intra-compartmental pressure, along with an unattainable for the period preoperative complex laboratory analyses[34] for immediate surgical fasciotomy intervention to decompress the limb from the danger of a developing compartment syndrome[35], as it is known in modern medicine, would have resulted in morbidity for the patient from rhabdomyolysis (decomposition process) of the skeletal muscles, leading to excessive presence of the myoglobin protein in the circulatory and urinary systems, causing complications with renal failure and ultimately death[36, 37]. Secondly, equally important, through the implementation of this specific ancient procedure, it empirically avoided the formation of fibrous connective tissue between the fractured bones, that is, the development of a therapeutic defect of the bone to be healed, known in modern orthopaedics as non-union[38], which in antiquity could be caused by infection or due to

---

[33] There are four fundamental leg muscle compartments, the anterior, the lateral, the deep and the superficial posterior.

[34] Mortensen, S.J., Vora, M.M., Mohamadi, A., Wright, C.L., Hanna, P., Lechtig, A., Egan, J., Williamson, P.M., Wixted, J.J., Rutkove, S.B., Nazarian, A., (2019), "Diagnostic Modalities for Acute Compartment Syndrome of the Extremities: A Systematic Review", *JAMA Surgery*, 154:7, p. 655-665.

[35] Gourgiotis, S., Villias, C., Germanos, S., Foukas, A., and Ridolfini, M.P., (2007), "Acute limb compartment syndrome: a review" *Journal of Surgical Education*, 64, p. 178–186; Park, S., Ahn, J., Gee, A.O., Kuntz, A.F., and Esterhai, J.L., (2009), "Compartment syndrome in tibial fractures", *Journal of Orthopaedic Trauma*, 23, p.514–518; Mauser, N., Gissel, H., Henderson, C., Hao, J., Hak, D., and Mauffrey, C., (2013), "Acute Lower-leg Compartment Syndrome", *Orthopaedics*, 36, p.619–624; Elliott, K.G., and Johnstone, A.J., (2003), "Diagnosing acute compartment syndrome: *The Journal of Bone and Joint Surgery. British volume*, 85:5, p. 625-32.

[36] Elliott, K.G., and Johnstone, A.J., (2003), "Diagnosing acute compartment syndrome", *Journal of Bone and Joint Surgery. British volume*, 85: 5, p. 625-32; McQueen, M.M., and Duckworth, A.D., (2014), "The diagnosis of acute compartment syndrome: a review", *European Journal of Trauma and Emerg Surgery*, 40: 5, p.521-8; Torlincasi, A.M., Lopez, R.A., and Waseem, M., (2023) "Acute Compartment Syndrome" [Updated 2023 Jan 16]. In: *StatPearls*, available through: https://www.ncbi.nlm.nih.gov/books/NBK448124/

[37] In modern medical science a postsurgical acute compartment syndrome therapy requires elaborate medical care g supported by systematic multidisciplinary treatments, cf. Glass, G.E., Staruch, R.M., Simmons, J., Lawton, G., Nanchahal, J., Jain, A., Hettiaratchy, S.P., (2016), "Managing missed lower extremity compartment syndrome in the physiologically stable patient: A systematic review and lessons from a Level I trauma center", *Journal of Trauma and Acute Care Surgery*, 81:2, p. 380-7; Maher, J.M., Brook, E.M., Chiodo, C., Smith, J., Bluman, E.M., and Matzkin, E.G., (2018), "Patient-Reported Outcomes Following Fasciotomy for Chronic Exertional Compartment Syndrome", *Foot & Ankle Specialist*, 11:5, p. 471-477.

[38] Megas, P., (2005), "Classification of non-union", *Injury*, 36: Suppl 4, S30–7; Giannoudis, P.V., and Papakostidis, C., (2006), "A review of the management of open fractures of the tibia and femur. *Journal of Bone Joint and Surgery. British volume*, 88:3, p. 281–9; Bell, A., Templeman, D., and Weinlein, J.C., (2016), "Nonunion of the Femur and Tibia: An Update", *Orthopaedic Clinics of North America*, 47:2, p. 365-75; Rupp, M., Biehl, C., Budak, M., Thormann, U., Heiss, C., and Alt, V., (2018), "Diaphyseal long bone nonunions - types, aetiology, economics, and treatment recommendations", International Orthopaedics, 42:2, p. 247-258; Nicholson, J.A., Makaram, N., Simpson, AHRW, and Keating, J.F., (2020), "Fracture nonunion in long bones: A literature review of risk factors and surgical management", *Injury*, 52 Suppl 2:S3-S11. http://doi.org/10.1016/j.injury.2020.11.029

extended edema that would result in the dissolution of the bone tissue and consequently osteonecrosis[39].

It is concluded that the stage of the therapeutic treatment involving the intermittent three-day applications of the more tightly compressed dressing with wide bandages at the fracture site allowed for intervals of sufficient relaxation[40] aimed at the perfusion of musculoskeletal tissues and thus preventing their necrosis, while it impeded the focal formation of extensive edema and the development of non-union of the bones.

Be that as it may, could there have been additional factors involved in the healing of the fracture with this specific therapy that were to remain unexplained in antiquity, apart from the empirical understanding of the treatment's advantages? In a review of the therapeutic procedure for the healing of fractured bones, which methodically involved tighter dressing- hence an unambiguous application of compressive forces at the fracture site, repeated attentively in three-day intervals, it has been understood through biomedical research since the second half of the last century[41], that potential electrical charges stimulate the osteoblastic activity toward the deposition of new bone materials, yet also the osteoclastic activity in the resorption process of bone[42].

This Hippocratic application method of mechanical compression through repeated and progressively increasing tighter dressing at the fracture site had the stimulating effect of generating an electro-negative potential, by inducing the piezoelectric properties of the collagen within the bone cells[43], known as mechano-transduction, the transformation from compressive strain to electrochemical activity, which enhanced osteoblastic activity, favoring

---

[39] Calori, G.M., Albisetti, W., Agus, A., Iori, S., and Tagliabue, L., (2007), "Risk factors contributing to fracture non-unions", *Injury*, 38 Suppl 2: S11-8; Pavelka, K., (2000), "Osteonecrosis", *Bailliere's Clinical Rheumatology*

14: 2, p. 399-414.

[40] Hippocrates, Volume III, On Fractures (1999), (Ed.) G. P. Goold, (Transl.) E. T. Withington, Loeb Classical Library, Harvard University Press, Cambridge, Massachusetts, LXVIII., 17-20, p. 196-197.

[41] Fukada, E., and Yasuda, I., (1957), "On the piezoelectric effect of bone", *Journal of the Physical Society of Japan*, 12, p. 1158–1162; A. Gjelsvik, A., (1973), "Bone remodeling and piezoelectricity- I", *Journal of Biomechanics*, 6, p. 69–77; Pollack, S.R.; Korostoff, E., Starkebaum, W., and Lannicone, W. (1979). "Micro-Electrical Studies of Stress-Generated Potentials in Bone". In (eds.) C.T. Brighton, J. Black, and S.R. Pollack. Electrical Properties of Bone and Cartilage. New York, Grune & Stratton.

[42] Cerrolaza, M., Duarte, V., and Garz´on-Alvarado,D., (2017), "Analysis of bone remodeling under

piezoelectricity effects using boundary elements", *Journal of Bionic Engineering*, 14, p. 659–671; Tandon, B., Blaker, L.L., and Cartmell, H.S., (2018), "Piezoelectric Materials as Stimulatory Biomedical Materials and Scaffolds for Bone Repair", https://doi.org/10.1016/j.actbio.2018.04.026; Mohammadkhah, M., Marinkovic, D., Zehn, M., and Checa, S., (2019), "A review on computer modeling of bone piezoelectricity and its application to bone adaptation and regeneration, *Bone*, 127, p. 544–555; Oladapo. B. I., Ismail, S.O., Kayode, J.F., and Ikumapayi, O. M., (2023), "Piezoelectric effects on bone modeling for enhanced sustainability", *Materials Chemistry and Physics,* 305, https://doi.org/10.1016/j.matchemphys.2023.127960.

[43] The non-centrosymmetric structure of collagen presents a polar uniaxial orientation of its molecular dipoles, considered as bioelectric when a number of its molecules correspondingly under the application of compressive forces they act to displace a significant number of electric charge-carriers from the interior to the surface of the bone component. In this way the bone exhibits piezoelectric capabilities in benefit of osteoblastic, bone remodeling/regenerative, activity, cf. Khare, D., Basu, B., and Dubey, A. K., (2020), "Electrical stimulation and piezoelectric biomaterials for bone tissue engineering applications", *Biomaterials*, 258, https://doi.org/10.1016/j.biomaterials.2020.120280.

bone remodeling[44] and thus favorable toward ossification[45]. Thus, in addition to the physiologically reduced blood flow in the region of the fracture due to vascular disruption[46], the effect of piezoelectric stimulation, induced by the gradually tighter dressing successively between the three-day intervals at the fracture site, augmented the osteoblastic activity by reducing oxygen concentration and increasing local tissue pH, both of which acted in favor of the regeneration and ossification of the fractured bones.

Recommendation

While the general understanding of the influence and adaptation of bones to external mechanical loads dates back to the late 1880s[47], the confirmation of the piezoelectric effect on bone since 1957[48], and the molecular support for bone ossification and remodeling since the 1970s[49], the earliest discernment through empirical testing of the orthopaedic regimen's favorable outcomes derived from the perceived advantages of the healing of long bone fractures, contingent upon a fundamental intervention principle of sequenced applications of increased pressure forces through tighter dressing at the fracture site-which were inducing the curative effects through bone piezoelectricity, should be recognized for the record of medical history as originating from the Hippocratic therapeutic treatment "On Fractures" (*Περί Αγμών*). It should be noted that following the relatively recent molecular medical substantiation of the beneficial properties of piezoelectricity in bones, the stimulation of bone tissue with electrical charges has become a highly effective, non-surgical, intervention method in bone healing and the treatment of non-union cases in fractures[50].

---

[44] Duncan, R.L., and Turner, C.H., (1995), "Mechanotransduction and the functional response of bone to mechanical strain", *Calcified Tissue International*, 57: 5, p. 344-58; Huang, C., and Ogawa, R., (2010), "Mechanotransduction in bone repair and regeneration", *Federation of American Societies for Experimental Biology Journal*, 24:10, p. 3625-32, https://doi.org/10.1096/fj.10-157370; Yavropoulou, M.P., Yovos, J.G., (2016), "The molecular basis of bone mechanotransduction", Journal of Musculoskeletal and Neuronal Interactions, 16:3, p. 221-36.

[45] Conversely, electropositive potentials are created by tensile forces that favor bone resorption through osteoclastic activity.

[46] It starts to recover in about two weeks and gradually normalizes by five months.

[47] Wolff, J., (1982). Das Gezetz der Transformation der Knochen, A. Hirschwald, Berlin, In (eds.) P. Manquet, and R. Furlong, (1986), The Law of Bone Remodeling, Berlin, Springer.

[48] Fukada, E., and Yasuda, I., (1957), "On the piezoelectric effect of bone", *Journal of the Physical Society of Japan*, 12:1158-62.

[49] Pollack, S.R., Korostoff, E., Starkebaum, W., and Lannicone, W. (1979), "Micro-Electrical Studies of Stress-Generated Potentials in Bone", In (eds.) C.T. Brighton, J. Black, and S.R. Pollack. Electrical Properties of Bone and Cartilage, New York, Grune & Stratton.

[50] Gupta, A. K., Srivastava, K.P., and Avasthi, S., (2009), "Pulsed electromagnetic stimulation in nonunion of tibial diaphyseal fractures", *Indian Journal of Orthopaedics*", 43:2, p. 156-60; Isaacson, B.M., and Bloebaum, R.D., (2010), "Bone bioelectricity: What have we learned in the past 160 years?", *Journal of Biomedical Materials Research*, https://doi.org/10.1002/jbm.a.32905; Khare, D., Basu, B., and Dubey, A. K., (2020), "Electrical stimulation and piezoelectric biomaterials for bone tissue engineering applications", *Biomaterials*, 258, 120280, https://doi.org/10.1016/j.biomaterials.2020.120280; Yang, C., Ji, J., Lv, Y., Li, Z., and Luo, D., (2022), "Application of Piezoelectric Material and Devices in Bone Regeneration", *Nanomaterials*, 12:24, 4386 https://doi.org/10.3390/nano12244386; Oladapo. B. I., Ismail, S.O., Kayode, J.F., and Ikumapayi, O. M., (2023), "Piezoelectric effects on bone modeling for enhanced sustainability", Materials Chemistry and Physics, 305, https://doi.org/10.1016/j.matchemphys.2023.127960

On orthopaedic splints, and surgical knots of Heraklas in Oreibasius

In addition to any procedure of spiral wrapping of bandages that could have been applied, with increased pressure application on the fracture site after the alignment of the diaphyseal bone fragments according to the Hippocratic regimen, the morpho-anatomic condition at the locus of what developed into the callus region, on the anterior surface of the Paliokastro skeletal tibial diaphysis, clearly reveals that a stabilization splint of rigid material was used to orthopaedically support the injured limb (Fig. 4). From the characteristic traces of this manifestation, it can be deduced that a flat rather than a tubular splint was used, a fact that agrees with the Hippocratic recommendations rather than the descriptive references of Celsus (25 BC - 50 AD) [51] where he exceptionally mentions the use of a tubular splint with side perforations for the use of straps to stabilize it to the limb for fractures of the tibia and femur. Conversely, the Hippocratic recommendations warned against the use of wooden tubular-type casts that were to be fitted only in the posterior part of the lower limb because, based on experience, they could not provide proper stability and immobility in favor of the aligned bones of the diaphysis, resulting in their misalignment due to the bodily movements of an inattentive patient[52]. Moreover, it recommended that for the stabilization of the aligned diaphyseal bones of a tibia, a preference for the careful placement of partial splints, around the bandaged area of the fracture, carefully and properly lined up in relation to the ankle joint and the tendon in the back of the leg (the Achilles tendon)[53] should be used.

However, there were no descriptions in “On Fractures” specifying the tying type of the splints in securing the orthopaedic stabilization, for example in the case of a fractured tibial diaphysis. Thankfully, the works of Oreibasius (320-403 AD)[54], the Greek personal physician of Emperor Julian (355-363 AD)[55], retained a remarkable set of records on this matter. At the urging of Julian, Oreibasius compiled two archival collections to assemble and

[51] Agelarakis, A. P., (2020), Eastern Roman Mounted Archers and Extraordinary Medico-Surgical Interventions at Paliokastro in Thasos Island during the ProtoByzantine Period, The Historical and Medical History Records

and the Archaeo-Anthropological Evidence, Archaeopress, Oxford, p. 16-22.

[52] Hippocrates, Volume III, On Fractures (1999), (Ed.) G. P. Goold, (Transl.) E. T. Withington, Loeb Classical Library, Harvard University Press, Cambridge, Massachusetts, XVI. 17-35, p. 136-138. While it was recognizing the usefulness of wooden tubular splints for the easier changing of bed sheets and for an easier transfer of the patient to the latrine, ibid. 28-30, p. 138.

[53] Ibid. XVI. 52-58, p. 138.

[54] An eminent iatrosophist of the 4th century, born in Pergamon, studied medicine and rhetoric in Alexandria, an admirer of Galen with expertise in pharmacology, surgery, and post-operative bandaging. He also served as *quaestor* of Constantinople and Emperor Julian’s political adviser and sacred ambassador, cf. Perdicoyianni-Paleologou, H., (2021), “Oribasius”, World History Encyclopedia, https://www.worldhistory.org/Oribasius/

[55] Iulianus Claudius Flavius, nephew of Constantin I, was the last member of the Constantinian dynasty (331-363), an illustrious Neoplatonic philosopher yet accomplished in political reform and successful in military campaigns he served as “Caesar of the West” (355-360), and as Augustus between 361-363. He fell in battle in Sassanid territory mortally wounded, fighting in the front lines and without wearing armor, in the abdominal region by a spear although Oreibasius attentively treated the wounds by suturing (*gastrorraphia*) the lower lobe of the liver, the affected intestines, and the parietal and greater peritoneum. Aspects of his legacy in attempts for religious reform in the Roman Empire may be reflected through his *School* and *Tolerance Edicts* in his efforts to reinstate polytheism against the dominance of Christianity, cf. New World Encyclopedia, (2023), "Julian the Apostate", https://www.newworldencyclopedia.org/p/index.php?title=Julian_the_Apostate&oldid=1080842

preserve the most important samples of ancient medical heritage, consisting of the writings, and excerpts of the works of earlier eminent medical practitioners. While, of these, the collection of Galen's works[56] (2nd-3rd century) has not been preserved, Book 48 out of the 72 of Oreibasius' *Ἰατρικαί Συναγωγαί* (*Collectiones medicae*) however, contains a chapter entitled *Υπό του Ηρακλᾶ* (of Heraklas) with descriptions and explanations of 16 surgical-orthopaedic knots[57] and bandages by the physician Heraklas of the 1st century, thus elucidating aspects of this subject of the orthopaedic process of stabilization of multiple splints. It should be noted that while several of the specific knots are still employed in contemporary medical practice, Heraklas recommended the nautical knot for securing splints in tibial diaphyseal fractures, ibid, (Fig. 5).

During our experimentations, aimed at understanding the execution and efficacy of the knot, it was observed that it could be easily and effectively applied[58], does not slip, remains stable, and maintains its integrity retaining its hold through the movements of a patient's bandaged limb in an orthopaedic resting position, especially when using leather straps, braided rope, and even strips of cloth bandages in tying the knot. Further, just an overhand loop[59] by the running end over the standing end of the strap while forming the knot structure creates a more robustly constrictive dressing (Fig. 6)[60] that remains firmly in place even during the upright movement (assisted or unassisted) of the injured person. Heraklas' surgical knots, with the potential pressure they would exert through the flat splints over the padding of tightly dressed bandages, could indeed yield comparable morpho-anatomic results in callus formation as manifested in the specific case of the Paliokastro healed fracture (Fig. 7) from the ProtoByzantine period.

---

[56] Galenos (*Galenus*) of Pergamon (129-216) one of the most important Greek philosopher physicians of antiquity; also served as the personal physician of the emperor Marcus Aurelius, Commodus, and Septimius Severus, cf. Agelarakis, A., (1997), "Galen", in (Ed.) F. Spencer, A World History of Physical Anthropology: An Encyclopedia, Garland, New York, p: 411-412; Nutton, V. "Galen", (2003), Encyclopedia Britannica, https://www.britannica.com/biography/Galen.

[57] Hage, J. Joris (April 2008), "Heraklas on Knots: Sixteen Surgical Nooses and Knots from the First Century A.D.", *World Journal of Surgery*, vol. 32, no. 4, pp. 648–655, doi:10.1007/s00268-007-9359-x

[58] Described for simplicity in five stages for securing the splints on the limb: 1. Place the standing part of the rope in front of the limb you face. 2. Take the running end of the rope and make a turn (over the limb) bringing it in the front of the limb. 3. Continue with the running end to crossover (an overhand loop) the standing part of the rope (either to the left or the right) forming an "X". 4. Continue with the running end of the rope making an additional turn over the limb (bringing it in the front of the limb), and without making an overhand loop, pass it straight under the "X". 5. Tighten the rope to secure the knot.

[59] Described for simplicity in five stages for securing the splints on the limb: 1. Place the standing part of the rope in front of the limb you face. 2. Take the running end of the rope and make a turn (over the limb) bringing it in the front of the limb. 3. Continue with the running end to crossover (an overhand loop) the standing part of the rope (either to the left or the right) forming an "X". 4. Continue with the running end of the rope making an additional turn over the limb (bringing it in the front of the limb), and continuing crossover (make an overhand loop) the standing part, then pass it straight under the "X". 5. Tighten the rope to secure the knot.

[60] In Figure 5, the second from the left knot is of type "B", as depicted in Figure 6.

Epilogue

The archaeological findings of the Paliokastro site at the Rachoni area of Thasos Island have preserved a rare record of palaeopathological evidence for the history of medicine, making it possible to reflect on aspects of the Eastern Roman-ProtoByzantine period's capabilities of physicians and surgeons on the interventional and orthopaedic processes implemented for the successful recovery from long bone fractures.

Further, on a broader scope, the tangible essence of therapeutic elements demonstrable through the anthropological record has provided a unique opportunity to appraise in conjunction with medico-historical sources a legacy of diachronic interconnections since the Hippocratic corpus on method, practice, and outcomes for the healing of fractured limbs, recognizable as beneficial foundations in the service of modern medical science.

Moreover, in a more focal perspective of this undertaking, it was remarkable to document the discrete instructions provided in "On Fractures" of the empirical implementation of piezoelectric forces through post-surgical fracture bandaging, considering the favorable effects of piezoelectric materials and devices applied by modern medicine and biomedical engineering in bone regeneration toward the reparative process in fracture union.

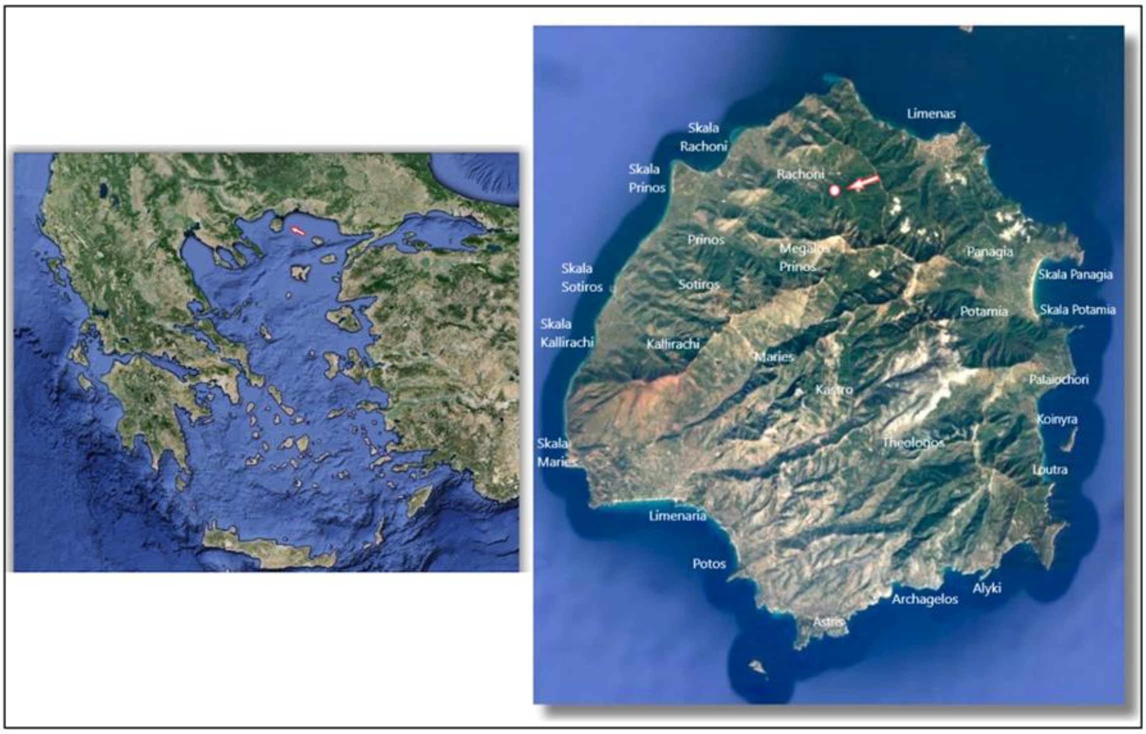

Figure 1. Map of Greece showing (arrow) Thasos Island within the Aegean Archipelago, and Thasos Island showing (arrow) the region of Rachoni and the location of the Paliokastro site.

Figure 2. Tibial bone diaphyses with manifestations of healed fracture areas.

Figure 3. X-ray image reflecting at the opaque regions of the trauma regions (arrows) the satisfactory reparative state of the osseous tissue.

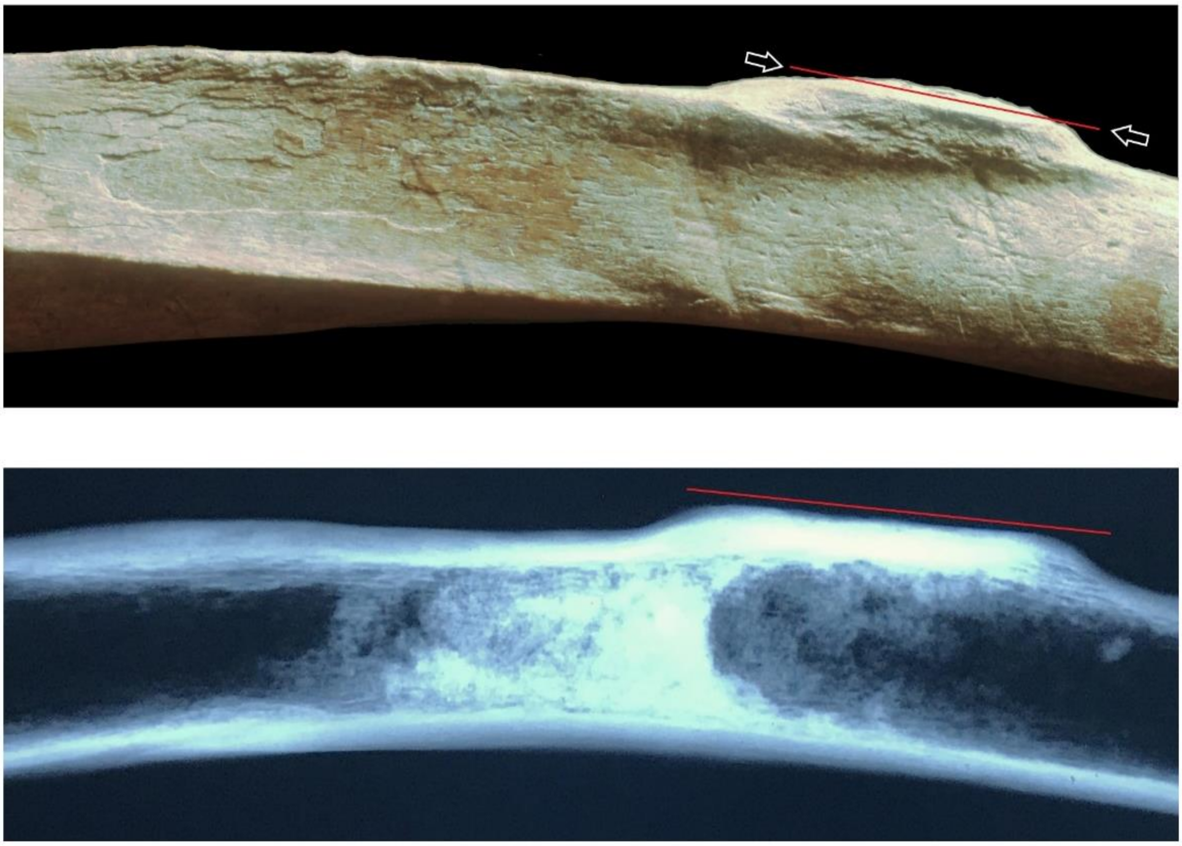

Figure 4. Bone surface anatomic morphology and X-ray image reveal that a flat splint of rigid material was used to orthopaedically support the injured limb at the locus of fracture.

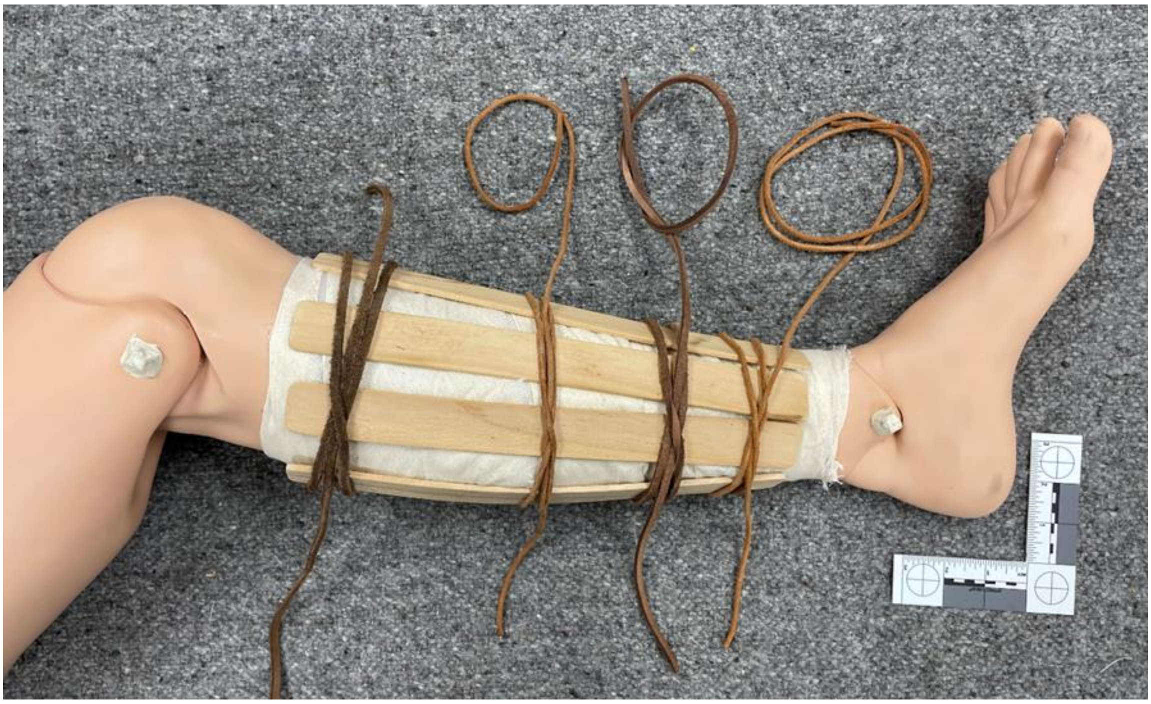

Figure 5. A model of a human left lower limb bandaged, dressed in sturdy yet flexible splints made of pine wood, and secured with leather bands of different shapes and thicknesses using Heraklas' nautical knot, except for the second from the left knot which is demonstrated in Figure 6:B (infra).

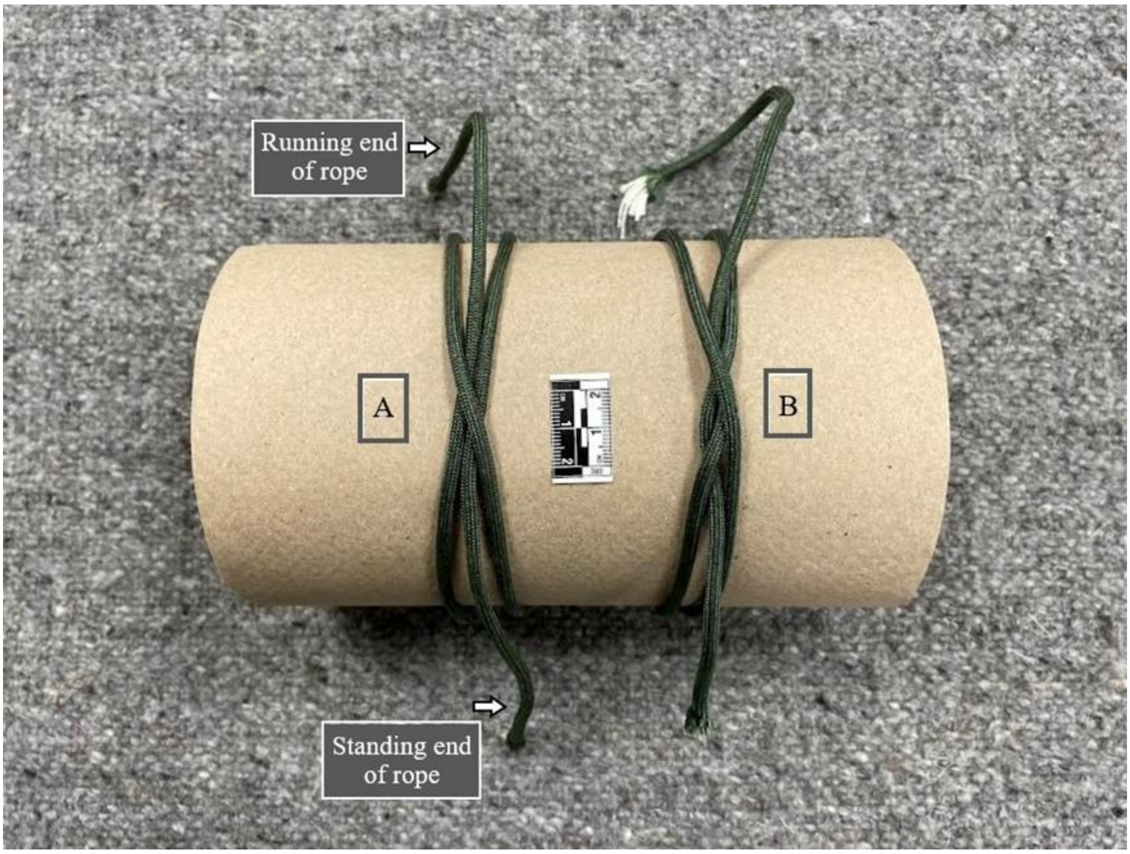

Figure 6. Heraklas' nautical knot for securing splinting applications is depicted as type A (left), while type B (right) illustrates an overhand loop variant in the knot structure.

Figure 7. Close-up view of the flattened bone callus morphology at the locus of the fracture site.