

BIOMECHANICAL BEHAVIOR OF THE TIBIOFIBULAR FRAME IN NONUNION

by R. GUNZBURG*, S. BOULVIN*, R. BOURGEOIS** and J. WAGNER*

In this paper an in vitro investigation of the biomechanical behavior of the tibiofibular frame in nonunion using electrical extensometry is presented. The intact and untreated nonunited frames are studied as well as three surgical treatments classically used in nonunion : the plating technique, the onlay graft technique and the external fixation according to Ilizarov. The monopodal position with extended knee is considered, and particular attention is paid to the different muscle insertions.

The results for the plating and onlay grafting techniques resemble those for the intact frame, whereas the Ilizarov external fixator increases the overall rigidity of the frame. In the untreated nonunited tibiofibular frame, an inversion of the tension and compression areas at the level of the tibia was found. We hypothesize that this phenomenon could be one of the mechanical factors leading to nonunion. Indeed, cyclic stresses in the fracture callus might prevent bony fusion, for the areas healing under compression stresses must become tension areas once the tibia is healed and vice versa.

Keywords : nonunion ; extensometry ; pathogenesis.
Mots-clés : pseudarthrose ; étiopathogénie ; extensométrie.

RÉSUMÉ

R. GUNZBURG, S. BOULVIN, R. BOURGEOIS et J. WAGNER. Comportement biomécanique du cadre tibio-péronier en pseudarthrose.

Une étude du comportement biomécanique du cadre tibio-péronier en pseudarthrose au moyen d'extensométrie électrique in vitro est présentée.

Le cadre intact et le cadre en pseudarthrose non traitée sont étudiés ainsi que trois traitements chirurgicaux de la pseudarthrose : plaque vissée, greffe

en "onlay" et fixateur externe d'Ilizarov. Le travail est effectué sur un montage en position monopodique, genou étendu, et une attention particulière est portée aux différentes insertions musculaires.

Les résultats pour la plaque vissée et la greffe en "onlay" ressemblent à ceux du cadre intact. Par contre, avec le fixateur externe d'Ilizarov, la rigidité du cadre augmente globalement. Dans le cadre pseudarthrosique non traité, l'on observe une inversion des zones en tension et en compression.

L'hypothèse est avancée que ce phénomène pourrait être un des facteurs mécaniques conduisant à une pseudarthrose. En effet, des contraintes cycliques au sein d'un cal fracturaire pourraient prévenir la fusion osseuse, car les zones en voie de guérison soumises à des forces de compression doivent devenir des zones soumises à des forces de tension une fois que le tibia est guéri et inversement.

SAMENVATTING

R. GUNZBURG, S. BOULVIN, R. BOURGEOIS en J. WAGNER. Biomechanisch gedrag van het tibio-fibulair kader in pseudarthrose.

Een in vitro studie aan de hand van elektrische extensometrie van het biomechanisch gedrag van het tibio-fibulair kader bij pseudarthrosen wordt voorgesteld. Het intacte kader en het kader bij pseudarthrose worden onderzocht, alsook drie heelkundige behandelingen bij pseudarthrosen : plating, "onlay" bottenten en externe fixatie volgens Ilizarov. Het werk werd uitgevoerd in monopodale positie met

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gestrekte knie en bijzondere aandacht werd geschonken aan de verschillende spieraanhechtingen.

De resultaten voor plating en onlay botenten gelijken op deze bekomen met het intacte kader. Met de Ilizarov uitwendige fixator daarentegen verhoogde de algemene rigiditeit van het kader. In de niet behandelde tibiofibulaire pseudarthrosen werd een inversie vastgesteld van de tensie en compressiegebieden ter hoogte van de tibia. De hypothese wordt geformuleerd dat dit fenomeen één van de mechanische factoren zou kunnen zijn die leiden tot een pseudarthrose. Cyclische ladingen ter hoogte van een fractuur-callus zouden inderdaad de heling kunnen verhinderen, daar de gebieden die onder compressie staan uiteindelijk in tensie moeten komen na genezing van de tibia en vice versa.

INTRODUCTION

Nonunion of the tibia has remained a problem for the orthopedic surgeon even though many diverse treatments have been suggested and developed. With the evolution of orthopedics in general and the better understanding of pathological phenomena in particular, more and more attention has been given to the biomechanical aspects of the disease. The biomechanical importance of the fibula has been sufficiently emphasized (6, 11, 12, 16, 18, 19, 20).

The aim of this paper is to compare the biomechanical behavior of this tibiofibular frame as a whole and not of the nonunion site itself. Three different surgical types of fixation classically used in nonunion are considered :

- a) plating (15),
- b) onlay bone grafting (2, 3), and
- c) external fixation according to Ilizarov (4).

MATERIAL AND METHODS

Bone and muscle representation

A tibiofibular frame from a normal 48-year-old man was stripped of all its connective tissues after which it was dried and radiographed to exclude any gross structural abnormality. Both bones were glued together with some elasticity at the level of

their joints in order to simulate their natural inter-relationship. The tibiofibular frame was mounted in a loading cage (fig. 1).

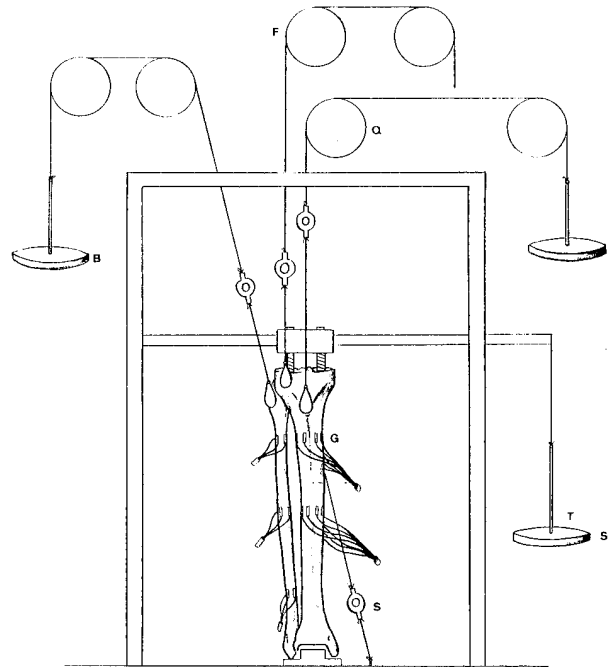


Fig. 1. — Drawing of the tibiofibular frame with strain gauges.

B : biceps loading scale ; F : fascia lata loading scale ; Q : quadriceps loading scale ; T : tibial plateau loading scale ; G : strain gauges.

Only the monopodal position with extended knee was considered in this paper, and here two muscles influence the mechanical behavior of the tibiofibular frame : the biceps femoris (1) and the tensor fascia lata (13). The action of the quadriceps and soleus muscles can be ignored when the extended knee position is being considered (20).

These four muscles were simulated at their exact insertion site by thin metal plates which were molded to the bone and glued to it with araldite. The muscle pulls were attached to these plates and their direction followed strictly the anatomical direction of the muscle fibers they represented.

Surgical setups

Before the actual surgical setups, two preliminary situations were considered :

- the intact frame as a reference
- the frame complicated by an untreated non-unioned tibial fracture.

In order to simulate this last situation, a 4-mm slice was removed from the tibia at the junction of its middle and lower third. The defect was filled with a 4-mm thick cancellous bone graft taken from the contralateral tibial metaphysis.

The three setups were then carried out.

The first one was the plating technique. A 6-hole AO plate was fixed to the anteromedial surface of the tibia with 6 screws.

The second one was the onlay grafting technique performed with a cortical bone graft of 125 mm × 15 mm × 4 mm, also taken from the contralateral tibia. The graft was fixed on to the same anteromedial surface, again with 6 screws.

Finally an Ilizarov type of external fixator was used. Two rings were placed on either side of the nonunion site, and an osteotomy of the fibula was performed at the level of the junction of its middle and lower thirds. The weight on the 1.8-mm diameter Kirschner wires was 130 kg. The compression placed on the nonunion site by the external fixator was judged arbitrarily in the same way as it is done clinically.

For these setups, the cancellous bone graft was left in the nonunion gap to simulate the cancellous tissues.

Measurement equipment and procedure

Twenty-three strain gauges (type TML PS3) were glued longitudinally at three circumferential levels on the frame. The 14 tibial gauges were placed in two levels of 7 gauges each, and the 9 fibular gauges in three levels of 3 gauges each. The two top fibular levels were opposite to the two tibial levels (fig. 2).

The recording of the diaphyseal strains was made with a Wheatstone bridge. To compensate for the thermal effects, all strain gauges were connected in half-bridge with dummy gauges glued on an unloaded bone.

The recording of the strains was made gauge by gauge after thermal stabilization, so as to reduce the influence of gauge drift. All recordings were done by the same person.



Fig. 2. — Radiograph of the tibiofibular frame with strain gauges.

Experimental setup and cycle of loading

The tibiofibular frame was placed in its loading cage, vertically in the frontal plane and inclined forward at 5 to 7° in the sagittal plane. The lower extremity of the frame rested on a semicylindrical

support to which it was perfectly adapted, allowing mobility of the frame in the sagittal plane.

The total tibiofibular load applied in the middle of each glenoid of the tibial plateau was transmitted via a lever at the extremity of which a loading scale was hooked.

To each muscle pull passing over a pulley, which was fixed to the cage, a loading scale was hooked as well. The real loads effected via these scales and their pulleys on their straps were measured by means of gauges connected in full bridge.

On each scale a preload of 0.5 kg was placed in order to stabilize the tibiofibular frame, to stretch the metal strings and to minimize losses due to friction over the pulleys. When the setup was loaded, weights were placed on the scale of the tibial plateau as well as that of the fascia lata and biceps femoris. The loads calculated by vector analysis (13, 17) for a man of 100 kg were : 200 kg for the tibiofemoral charge, and 150 kg for the lateral muscle group i.e. 100 kg for the fascia lata and 50 kg for the biceps femoris (20).

The measurements were made at 1/10 of the calculated charges. For the intact frame and the three treatments studied, a first measurement was made in preload, a second in load and a third again in preload. For the untreated nonunited frame, the measurements were made in preload only.

RESULTS

The results are represented as polar diagrams : a rectangle corresponding to the value of the strain is situated perpendicularly to the exact site on the cortex where it is recorded, the white rectangles corresponding to tension and the black ones to compression. For each gauge, the difference between measured values in load and in preload is represented. For the untreated nonunited frame, the given values are those obtained in preload after creation of the nonunion.

With the intact tibiofibular frame (fig. 3), the strains obtained when loading the frame show that the tibia and the lower part of the fibula are essentially loaded in flexion.

In the untreated nonunited tibiofibular frame (fig. 4), the whole fibula undergoes flexion. The

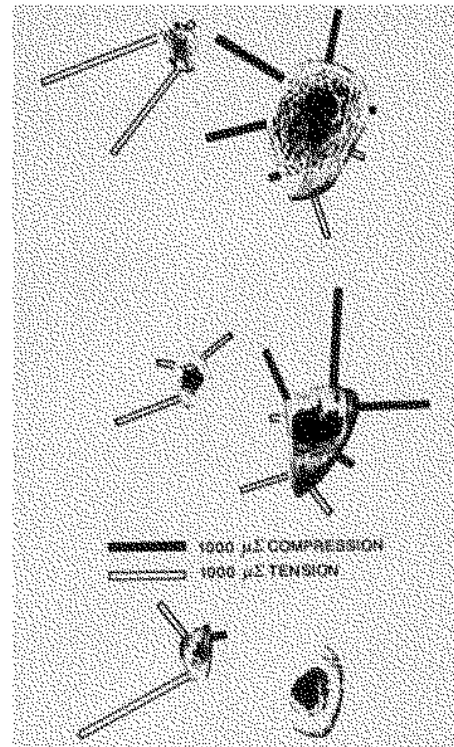


Fig. 3. — Polar strain diagram with the intact tibiofibular frame.

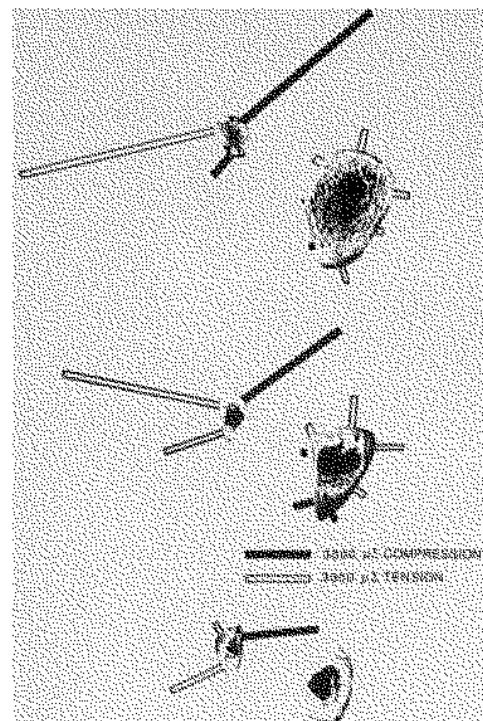


Fig. 4. — Polar strain diagram with untreated nonunion (note the different scale).

tibia remains in flexion as well, but a reversal of the signs of the stresses is observed. The anterior part comes under compression and the posterior part under tension. The absolute values of fibular strains are very high, whereas the tibial values are smaller.

With the plating technique (fig. 5), the values approximate those of the normal frame. The neutral planes are the same for the tibia. The fibula undergoes flexion in its upper and lower thirds; at the level of the middle third, only tension was recorded. Here the neutral planes approximate those of the untreated nonunited tibiofibular frame, but the absolute values of the strains are smaller.

With the onlay graft technique (fig. 6), the neutral planes are comparable to those obtained with the AO plate. The absolute values of strains measured on the tibia are smaller, whereas those measured on the fibula are higher.

Finally the external fixator of Ilizarov (fig. 7) gives tibial neutral planes approximating those of the intact frame. The absolute values are even smaller than those obtained with the plating technique, and the fibular stresses are all in tension.

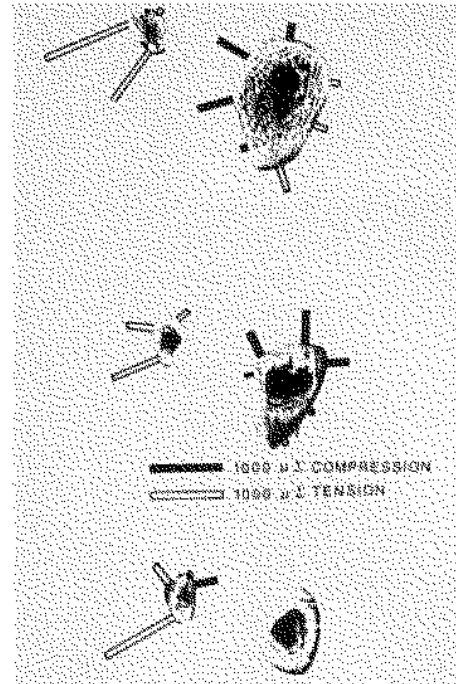


Fig. 6. — Polar strain diagram of the tibiofibular frame treated with onlay bone graft.

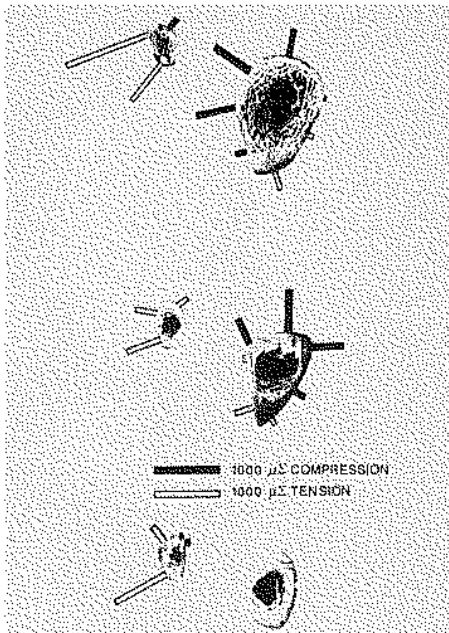


Fig. 5. — Polar strain diagram of the tibiofibular frame treated with AO plate.

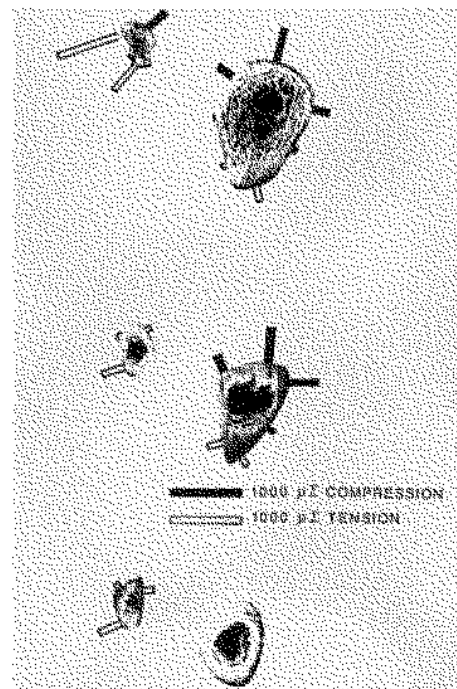


Fig. 7. — Polar strain diagram of the tibiofibular frame treated with the Ilizarov external fixator.

Table I

	Tibia		Fibula	
	Compression	Tension	Compression	Tension
Normal frame	1260	640	180	1570
Nonunion, untreated	820	1380	7850	10240
AO plate	650	290	180	1240
Onlay graft	500	350	270	1230
Ilizarov fixator	480	200	310	890

The extreme values of strains in tension as well as in compression for both bones are shown in table I.

DISCUSSION

Material and methods

The characteristics of dry bone differ greatly from living bone : the behavior of dry bone in varying situations can nevertheless be compared.

The choice of extensometry as the measurement technique was based on the studies made by Wagner (20) in that field. He showed that there is no significant topographic variation of the mechanical properties of cortical bone ; therefore we may consider the cortex as relatively homogeneous. Evans and King (5), on the other hand, showed that the cancellous part of the shaft of long bones can be ignored, as it has an elasticity modulus which is approximately 100 times less than that of cortical bone and that its role in the resistance (in flexion) can therefore be ignored.

The method of brittle coating (9, 10, 20) helps to situate the neutral plane. The anterior aspect of the tibia, for example, corresponds to a tension zone and the posterior aspect to a compression zone. On the basis of these data, a judicious choice for the positioning of the strain gauges could be made.

In the monopodal position, muscle action had to be introduced, for Wagner (20) showed that this brought about a redistribution of the strains in a tibiofibular frame previously loaded by a femorotibial charge.

The choice of muscle action was based on the vector analysis research of Maquet (13) and

Kummer (8), who emphasised the importance of the soleus, quadriceps and fascia lata, as well as on the electromyographic work of Blaimont *et al.* (1), who showed the importance of the biceps femoris in the lateral muscle group. In the monopodal position the quadriceps and soleus muscles are kept in preload, whereas the fascia lata and biceps femoris are loaded in a proportion of 2 to 1 for the fascia lata and biceps femoris as suggested by Wagner (20).

The femorotibial load is applied to the middle of each glenoid of the tibial plateau, which corresponds to the real support zones, as was shown by Maquet *et al.* (14) and Freeman (7).

The measurements were made at 1/10 of the calculated charges so as not to overload the frame. This is permissible, as Wagner (20) showed that the strains behave linearly.

Study of the different setups

The values obtained for the intact frame are similar to those obtained by Wagner (20), which shows that the technique can be reproduced.

In the untreated nonunion, the fibular strains are enormous, even in preload. The appearance of neutral planes over the whole length of the fibula seems to indicate that the fibula tries to take over the role of the tibia. In contrast with the normal frame where the fibular stresses are essentially in tension, in nonunion we find flexion. This redistribution of stresses goes together with a reversal of the sign of the tibial stresses. The posterior part of the bone becomes a tension area. This could well be one of the causes leading to a nonunion. To return to the normal mode of loading of the tibia, i.e. healing, the stresses must again change

their signs. We might even put forward the hypothesis that owing to cyclic stressing with the wrong signs, the formation of bone trabeculae in the fracture callus is prevented by the continuous destruction of these trabecular bridges, the trabeculae appearing in the tension zone having to be submitted ultimately to compression forces and vice versa.

Nearly all the stresses recorded on the tibiofibular frames treated according to the plating or onlay grafting techniques are of the same sign, but of lesser size than those measured on the intact frame. Their behavior resembles that of the intact frame. At a distance from the nonunion, the relationships appear to have been restored. As opposed to the plating technique, with the onlay grafting technique smaller strains are observed on the tibia and bigger ones on the fibula. This difference might be explained by the different rigidities of the cortical bone graft and metal plate. With the Ilizarov external fixator the strains are generally much smaller than in the intact frame or with the plating or grafting techniques. This reduction of stresses on the frame as a whole is due to the fact that by its structure the Ilizarov fixator influences a much larger zone of the tibiofibular frame. It makes it more rigid than in its normal status.

CONCLUSION

This experimental study showed that

1. in untreated nonunion the mechanical stresses on the tibia are reversed.
2. the plating and onlay grafting techniques restore the habitual mechanical properties of the tibiofibular frame, and
3. the external fixator of Ilizarov makes the tibiofibular frame very rigid.

Our study has encouraged us to investigate further the importance of the inversion of the sign of the tibial stresses in the pathogenesis of nonunion. There are, of course, other causes leading to nonunion, such as vascularization, the complexity of the fracture, and the soft tissues. A more extensive study on a cellular or molecular level would help give a better understanding of nonunion.

REFERENCES

1. BLAIMONT P., BURNOTTE J., BAILLON J. M., DUBY P. Contribution biomécanique à l'étude des conditions d'équilibre dans le genou normal et pathologique. Application du traitement de l'arthrose varisante. *Acta Orthop. Belg.*, 1971, 37, 573-591.
2. CAMPBELL W. C. The treatment of ununited fractures. *Am. J. Surg.*, 1923, 37, 1.
3. CAMPBELL W. C. Onlay bone graft in treatment of ununited fractures of long bones. *South. Med. J.*, 1927, 20, 107-114.
4. CATTANEO R., VILLA A., CATAGNI M., TENTORI L. Traitement des pseudarthroses diaphysaires septiques ou non septiques selon la méthode d'Ilizarov en compression monofocale. *Rev. Chir. Orthop.*, 1985, 71, 223-229.
5. EVANS F. G., KING A. *Regional differences in some physical properties of human spongy bone*. In: Biomechanical studies of the musculoskeletal system. C. C. Thomas, Springfield, 1961, p. 118.
6. EVANS F. G. *Mechanical properties of the bone*. C. C. Thomas, Springfield, 1973, p. 90, p. 121.
7. FREEMAN M. A. R. *The surgical anatomy and pathology of the arthritis knee*. In: *Arthritis of the knee*. Springer-Verlag, Berlin, Heidelberg, New York, 1980, pp. 31-56.
8. KUMMER B. Gait and posture under normal conditions with special reference to the lower limbs. *Clin. Orthop.*, 1962, 25, 32-41.
9. KUNTSCHER G. Die Darstellung des Kraftflusses im Knochen. *Zentralbl. Chir.*, 1934, 61, 2130-2136.
10. KUNTSCHER G. Die Bedeutung des Darstellung des Kraftflusses im Knochen. *Arch. Klin. Chir.*, 1935, 182, 489-551.
11. LAMBERT K. L. The weight bearing function of the fibula. A strain gauge study. *J. Bone Joint Surg.*, 1971, 53-A, 507-513.
12. LECESTRE P., BENOIT J., DABOS N., RAMADIER J. O. Les fractures de fatigue. À propos de 8 cas. *Rev. Chir. Orthop.*, 1977, 63, 815-824.
13. MAQUET P. *Biomechanics of the knee. With the application to the pathogenesis and the surgical treatment of osteoarthritis*. Springer-Verlag, Berlin, Heidelberg, New York, 1984, pp. 22-61.
14. MAQUET P., VAN DE BERG A., SIMONET J. Femoro-tibial weight-bearing areas. *J. Bone Joint Surg.*, 1975, 57-A, 766-771.
15. MULLER M. E. Treatment of nonunions by compression. *Clin. Orthop.*, 1965, 43, 83-92.
16. OLIVER S., NERUBAY J., KATZNELSON A. The fibula as a weight-bearing bone. *Harefuah*, 1973, 84, 490-493.
17. PAUWELS F. *Biomécanique de l'appareil moteur*. Springer-Verlag, Berlin, Heidelberg, New York, 1979, 198-228.
18. SOLARES R., VILLEGAS F., GUERRERO J. L.,

OLIVARES A., HERRERA G. Biomechanica del perone. In forme preliminar. *Prensa Med. Mex.*, 1974, 39, 453-460.

19. WAGNER J., BOURGEOIS R., HERMANNE A. *Bio-mécanique du cadre tibio-péronier : rôle mécanique et physiologique du péroné*. Cahiers d'enseignement de la SOFCOT 1983, Conférences d'enseignement, 2^e série, 101-114.
20. WAGNER J. *Contribution à l'étude biomécanique du*

cadre tibio-péronier. Thèse, Université Libre de Bruxelles, 1983, pp. 50-82.

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