Department of Veterans Affairs

Journal of Rehabilitation, Research and Development Vol. 27 No. 1
Pages 43–52

Special Article

Articulated cadaveric bones as a structural endoskeleton in an ankle-foot prosthesis: A preliminary report

Dr. S.G. Kabra, MS (Anat), MS (Gen Surg)
Rehabilitation Aids and Limb Fitting Centre, Santokba Durlabhji Memorial Hospital, Bhavani Singh Marg, Jaipur, India 302 015

EDITOR'S NOTE

The human ankle-foot system is still far more complex and functional than existing commercially available prostheses. In the following article the author provides a preliminary report on an experiment using articulated cadaveric bones as a structural endoskeleton in an ankle-foot prosthesis. The report is preliminary and does not support any final conclusions.

However, the study is unusually original and is published to stimulate thought and further research. The comments of two leading researchers are presented to help readers place the merits and limitations of this work in perspective.

Seldon P. Todd, Jr., Editor

This paper addresses a significant problem in prosthetics--that of replacing the complex function of the human foot with a prosthetic foot. The author has presented a novel, enticing idea for solving this problem. While the concept may be valid, this report is too preliminary to allow conclusions.

Boiled, dried bones are obviously devoid of sensory receptors and are devoid of remodelling capacity. Human bones, even with the capability to remodel, are known to fatigue and fail especially when devoid of dynamic muscle stabilization. Further, human bones, particularly in the foot, when devoid of sensory input are known to suffer degeneration in the form of Charcot joints, with marked destruction of the boney architecture.

Research needs to be done on methods of effective articulation between bone surfaces. Possible methods include maintenance of human cartilage and the vulcanization of rubber compounds into articulating surfaces. Unless the complex articulations present in the human ankle-foot complex are precisely duplicated in a prosthesis, normal motion will not occur, especially at the joints. Abnormal motion is bound to lead to destruction of the joint surfaces and further destruction of the bones will occur under repetitive loading conditions.

Quantitative measurements are needed on movements at various articulations and comparisons made of such movements with normal walking and other human functions. A quantitative comparison of the articulated bone prosthesis to the Jaipur Foot is also needed.

Harry B. Skinner, M.D., Ph.D.
Department of Orthopedic Surgery
University of California/San Francisco
Rehabilitation R&D, VA Medical Center
Fort Miley, San Francisco

DOI: 10.1682/JRRD.1990.01.0043

Journal of Rehabilitation Research and Development Vol. 27 No. 1 Winter 1990

The potential value of the following report by Dr. Kabra lies in its description of experimental methods for observing the mechanics of the bones and ligaments of the human foot under actual prosthetic use in a below-knee artificial limb. A better understanding of prosthetic foot function would allow us to improve prosthetic ankles and feet with the same inert materials we currently use for artificial limbs.

Dr. Kabra's study has been stimulated by the widespread use of the Jaipur Foot in India and in other third world areas. The Jaipur Foot is inexpensive to produce; it is a vulcanized rubber and fabric unit of simple design, which uses a wood keel. It is generally worn either barefoot or in a loose sandal. The unit is quite flexible and is especially useful as a barefoot device for individuals who desire to climb trees, walk in wet irrigated fields, and assume frequent squatting positions.

The research is too preliminary to provide scientific conclusions on the potential value of the articulated bone prosthesis as an improvement on the Jaipur Foot. As to the practical applications of this potential system, the following points may be made:

1) Sources of suitable and available human cadaveric feet are limited, especially in first world countries. Sizing of the feet for clinical use in itself would be a major drawback. Available feet, even in a country such as India, would have to be reasonably sized to be effective.

2) In theory, an individual's own foot could be used in some types of traumatic injury. However, the preparation of the foot for prosthetic use is very labor intensive and would be unsuitable for practical application on that basis alone.

3) The durability of the articulated cadaveric bone ankle-foot was not studied. The author states that long-term trials would be necessary. It was found that a reconstructed foot using exhumed skeletal bones was totally impractical, in that they fragmented when used for even a short period of time.

Ernest M. Burgess, M.D.
Director, Prosthetics Research Study
Seattle, Washington

Abstract—This report describes the construction and evaluation of an ankle-foot prosthesis using human cadaveric bones as the endoskeleton inside a fiber-reinforced vulcanized rubber shell. Cadaveric bones and exhumed skeletal bones were used. Three designs were fabricated, subjected to radiographic evaluation, and underwent 4-week field trials of normal daily use by a unilateral below-knee amputee. The rubber shell retained the position of the bones, permitted movements at the joints in various stages of the stance phase, and restored the bones to their neutral position when the foot was unloaded. The cadaveric prosthesis provided for plantar flexion of the foot when the heel was loaded and for locking of the joints to restrain excessive movement when the foot came to rest. While fresh cadaveric bones withstood all the stresses of active walking, exhumed macerated bones fractured and fragmented with use.

Key words: *ankle-foot prostheses; cadaveric bone endoskeleton; fiber-reinforced vulcanized rubber shell; Jaipur foot; SACH foot; SAFE foot.*

INTRODUCTION

The ankle-foot portion of the human lower limb is structurally and functionally a highly complex unit. It consists of 28 bones and 33 articulations. It has over 150 ligaments as elastic restraining structures and is under the active voluntary control of 31 suitably positioned muscles of varying power. The shapes of the tarsal and metatarsal bones, and their complex articulations into longitudinal and transverse arches, provide a versatile structural base for the independent, sequential, and associated movements that accompany human walking, running, jumping, and lifting of loads. These skeletal elements elegantly reconcile the two contradictory functional requirements of the foot: strength and rigidity for weight transmission, and resilience and flexibility for graceful gait. The skeletal articulations allow a large number of independent movements in different axes, but are structurally designed to provide for optimum range of motion at appropriate stages of the walking cycle. Thus, a part of the restraining attribute is inherent in the shape of the articulations themselves.

Address all correspondence and reprint requests to: Dr. S.G. Kabra, Director, Rehabilitation Aids and Limb Fitting Centre, Santokba Durlabhji Memorial Hospital, Bhavani Singh Marg, Jaipur, India 302 015.

The development of the cadaveric ankle-foot prostheses has proceeded in two directions: articulated and non-articulated ankle-foot units (2,4). In the articulated units, an attempt has been made to provide various movements by the incorporation of different types of uniaxial and multiaxial joints coupled with restoring devices. In the non-articulated ankle-foot units, selective flexibility and compressibility have been provided to the different parts of the prosthesis by incorporating variable stiffness materials, giving them functional attributes that simulate movements when the foot is loaded.

Several varieties of articulated and non-articulated ankle-foot prostheses are available. Among the most popular of the non-articulated type is the SACH (Solid Ankle Cushioned Heel) foot (1). In India, a unit called the Jaipur Foot is preferred. In articulated ankle-foot units, joints of different complexities provide for desired movements, while restraining and restoring attributes are provided by additional components. However, currently available articulated units are costly and their maintenance requirements, weight, and necessity of protection against dust when the ankle joint is externally located, limit their utility. At the present time, a low-cost, lightweight, and low-maintenance articulated ankle-foot unit simulating all the joints of a natural foot seems impossible.

OBJECTIVE

It was felt that a functionally near-natural prosthetic foot could be fabricated by replacing the wooden and microcellular rubber (MCR) inserts of a conventional Jaipur foot with an endoskeleton of articulated human ankle-foot bones. The present study was undertaken to explore the utility of such a prosthesis, addressing in particular the following questions:

1) Do dried bones have enough strength to withstand the stresses induced during walking and other activities?

2) Will the tire-cord reinforced rubber shell adequately retain the articulated ankle-foot bones in their respective appositions?

3) Do the required movements occur at the various articulations?

4) Does the external shell restore the bones to their neutral position after movement is complete and the foot returns to a resting condition?

5) How does such a foot compare functionally with the conventional Jaipur foot?

FABRICATION MATERIALS AND METHODS

Two types of articulated bones of the ankle and foot were obtained from the anatomy department of a medical college. They were: 1) exhumed, macerated cadaveric foot bones which were cleaned, boiled, dried, and re-articulated with copper wires; and 2) freshly dissected cadaveric feet, cleaned to the joint ligaments which held the bones in position, then boiled and dried. (No articulation with copper wires was required for these bones.) MCR sheets of hardness Shore A 35 were procured from local producers of rubber slippers. Rubber compounds for vulcanization were the same as used for tire-retreading, and were procured locally.

The method of fabrication was based on the method used for the fabrication of the Jaipur foot (3), in which the three inserts (i.e., fore-foot and heel of MCR sheets, and an ankle of laminated wood) are covered with a layer of rayon or nylon cord-reinforced unvulcanized rubber, and then vulcanized (**Figure 1**). However, in this study, three different designs were fabricated, with variations in the materials used in each.

Fabrication of the three designs

In design I, only the fore-foot MCR insert was replaced by an articulated distal row of tarsals, with metatarsals and phalanges. The heel insert and the ankle-block carriage-bolt assembly were the same as used in the Jaipur foot.

In design II, an entire articulated foot was used to replace both the heel and the fore-foot inserts. In this design, the Jaipur ankle-block carriage-bolt assembly was used but altered by shaping its lower end to conform to the articulating surface of the talus.

In design III, the tibiofibular mortise of the ankle joint was used along with the fore-foot and heel bones, replacing all the inserts. The ankle-block carriage-bolt assembly of a suitable reduced height was used. Its lower end was shaped and slotted to engage the upper ends of the tibia and fibula.

Journal of Rehabilitation Research and Development Vol. 27 No. 1 Winter 1990

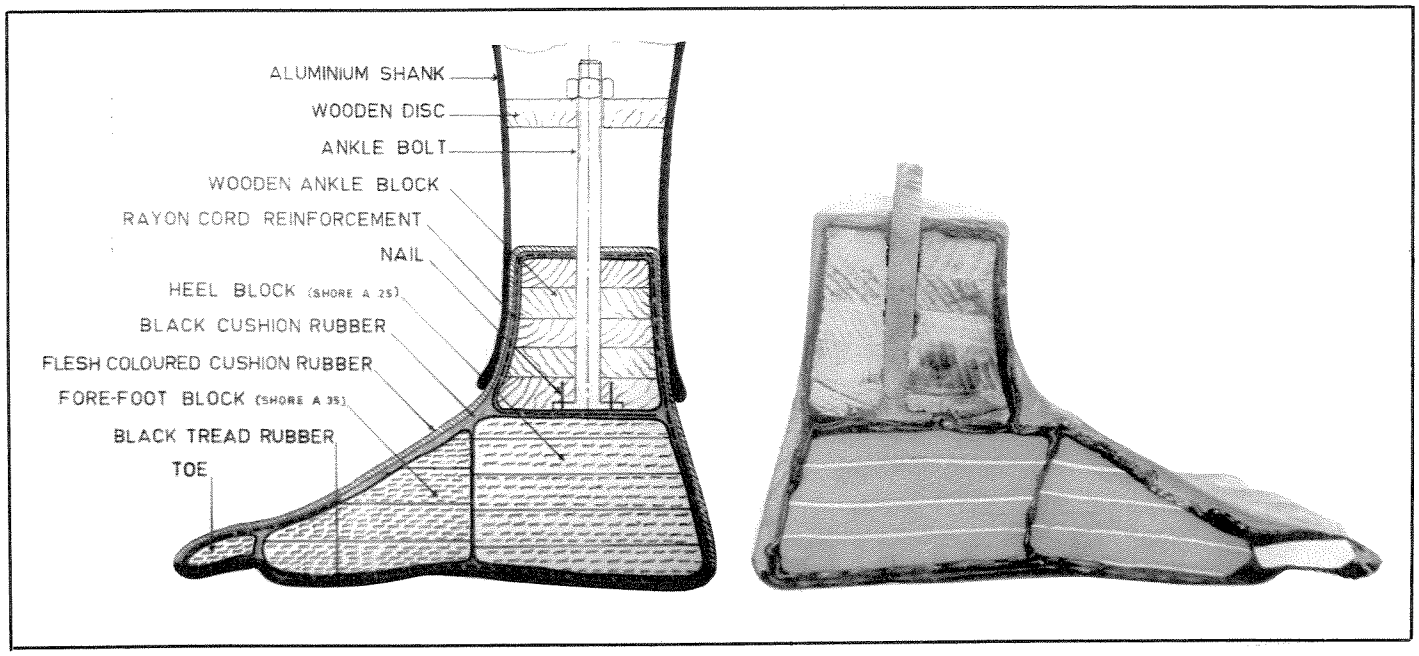


Figure 1a (left) and 1b (right).
The Jaipur foot. (a) Diagram of components. (b) Sagittal section of actual foot.

One ankle-foot assembly of each of the three designs was made using fresh cadaveric bones. One assembly of the design II was made using exhumed macerated bones. In each design, a suitably shaped microcellular rubber sheet was used below the calcaneum and to fill the concavity of the arched articulated foot bones.

The articulated skeletal elements of each design were painted with vulcanizing cement and then covered with a layer of black unvulcanized rubber compound. Reinforcing cord strips were laid across all joints. Two layers of black tread compound constituted the sole of the foot component. Two layers of skin-colored unvulcanized rubber were used as a cosmesis over the ankle and upper of the foot. The assembled feet were then vulcanized in steam for two hours at 120 degrees C at 175 kN/m^2 pressure. The completed ankle-foot assemblies weighed 800 to 830 g each. All of the designs conformed to a number 7 foot size.

TESTING

After gross physical testing of each foot for flexibility and complete vulcanization, dorso-ventral and lateral radiographs were taken. **Figures 2 and 3** show design II, using exhumed bones articulated with copper wire as endoskeleton. **Figure 4** shows design III, using fresh cadaveric bones as endoskeleton.

The subject who participated in the testing of the prostheses was a long-term unilateral below-knee amputee, who had been wearing a Jaipur Foot and aluminum socket. The fabricated ankle-foot prostheses were fitted to the aluminium shank of the subject's socket. After checking the alignment, each of the ankle-foot assemblies was evaluated by field trials. The subject used each of the assemblies for a period of 4 weeks. He walked an average of 5 km and cycled 15 km daily. He also wore the prostheses while performing various household chores, which involved lifting heavy loads.

In addition to the dorso-ventral and lateral radiographs of loading while standing, lateral radiographs of the same design II and III assemblies (shown in **Figures 2-4**) were taken under loading in four stance phase positions of the walking cycle:

1) The subject was asked to load the heel with his body weight (**Figures 5a and 5b**).

2) The subject then stood with the prosthetic foot fully grounded and the sound foot lifted off the ground (**Figures 6a and 6b**).

3) The subject stood on the prosthetic fore-foot while the sound foot was lifted off the ground (**Figures 7a and 7b**).

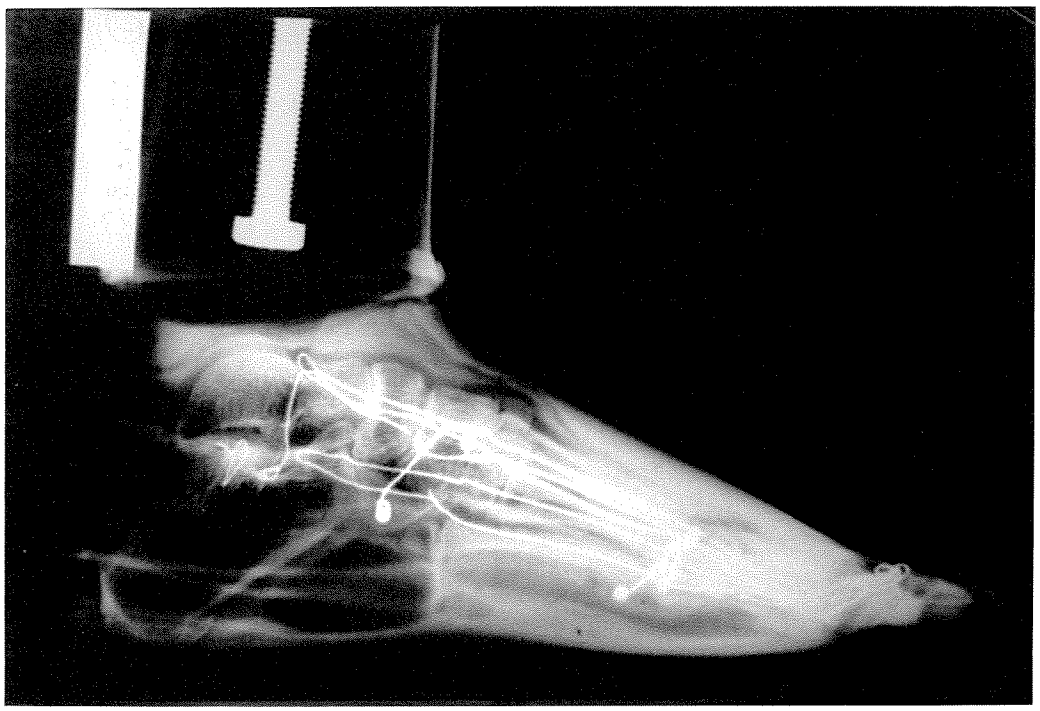


Figure 2.
Lateral radiograph of design II (exhumed bone endoskeleton articulated with copper wire). The design does not have an ankle joint. The wooden ankle-block is shaped to fit directly over the talus.

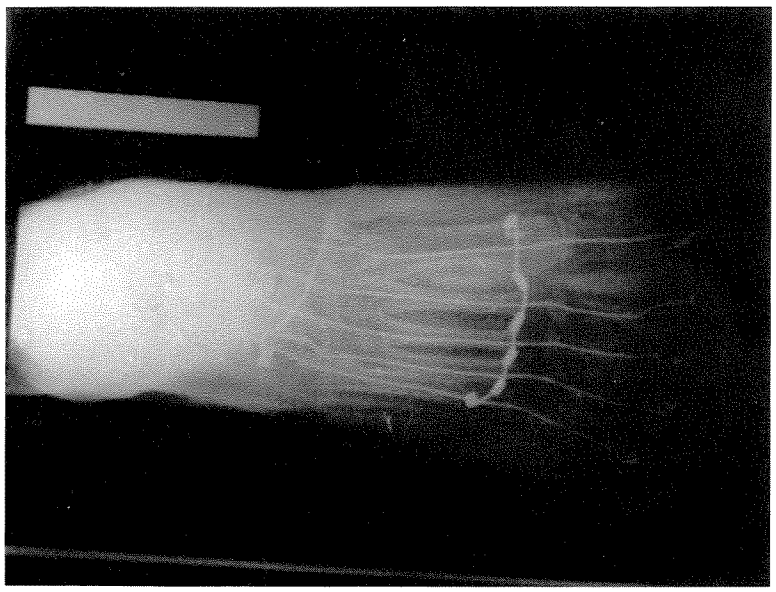


Figure 3.
Dorsoventral radiograph of design II. The position of the five rays is seen.

Figure 4.
Lateral radiograph of design III (fresh cadaveric bone endoskeleton). The articulations of the bones are retained in the same position in which they are present in the human foot.

4) The subject was asked to load the foot while a wooden block was placed under its lateral border **(Figures 8a and 8b)**.

The subject was generally satisfied with the test units. He specifically commented upon the greater flexibility of these prostheses as compared to the Jaipur foot and on the locking of movements at the right time provided by the test units.

RESULTS

Design I (fore-foot endoskeleton only replaced) showed greater pronation and supination when tested by loading the fore-foot against a wedge placed under the lateral or the medial border, respectively, of the foot. Design II (human bone fore-foot and heel) revealed greater eversion, inversion and dorsiflexion. Design III (human bone fore-foot, heel, and ankle joint tibiofibular mortise) showed plantar flexion in the heel-loaded position as well as eversion, inversion, and dorsiflexion. No differences in walking cycle and gait were noted when the endoskeletal prosthesis was compared to a standard Jaipur foot.

Radiographic studies of the human bone prosthetic feet revealed that the positions of the articulations paralleled those of the bones in a normal foot during the observed walking cycles. When loaded in various stages of the stance phase, the bones of the prosthetic foot showed movements at the different joints, as illustrated in **Figures 5-8**. When unloaded, the bones were restored to normal positions.

After the 4-week trial period of normal daily use, lateral radiographs were again taken of each foot. The repeat radiographs showed that the bones in design III (using fresh cadaveric bones) had remained intact and in their normal position **(Figure 9)**. However, the exhumed macerated bones used in design II showed multiple fractures and fragmentations **(Figure 10)**.

Figure 5a (left) and 5b (right).
(a) Design II. Lateral radiographic view showing heel of prosthetic foot loaded as sound limb is lifted. (b) Design III. Lateral radiographic view with heel of prosthetic foot loaded as sound limb is lifted, showing plantar flexion.

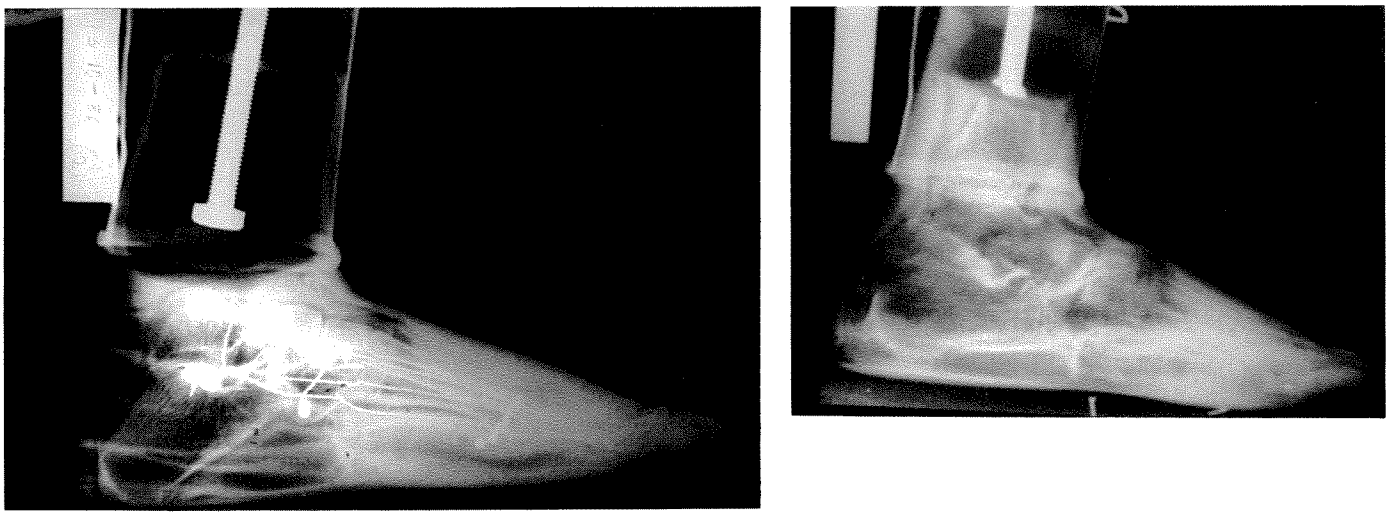


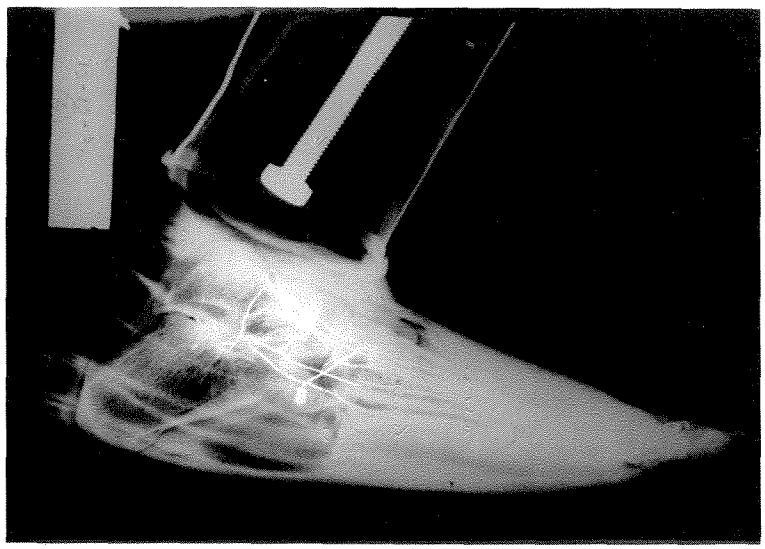
Figure 6a (left) and 6b (right).
(a) Design II. Sound limb is lifted and prosthetic foot is fully loaded. (b) Design III. Sound limb is lifted and prosthetic foot is fully loaded. The bones maintain their position and the longitudinal arch is maintained.

DISCUSSION

These preliminary experiments indicate that fresh, cadaveric ankle-foot bones possess sufficient strength to withstand the stresses of normal walking when used as an endoskeletal support inside a fabric-reinforced rubberized prosthetic foot. Exhumed macerated bones were shown to be unsuitable for this purpose.

The rubberized exterior, while being strong enough to retain the articulated bones in their respective apposition, is elastic enough to allow their movement when the foot is loaded and to restore them to a neutral position when unloaded. Thus, the

Journal of Rehabilitation Research and Development Vol. 27 No. 1 Winter 1990



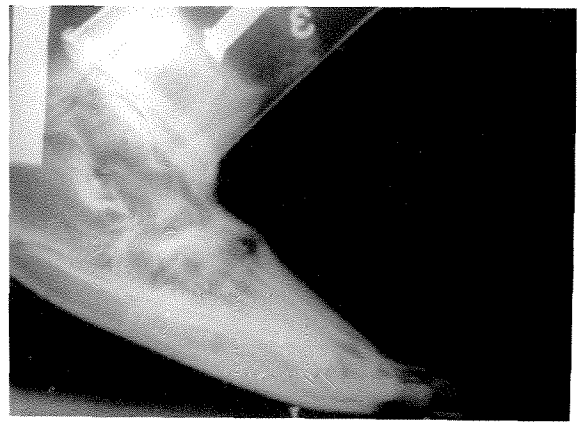
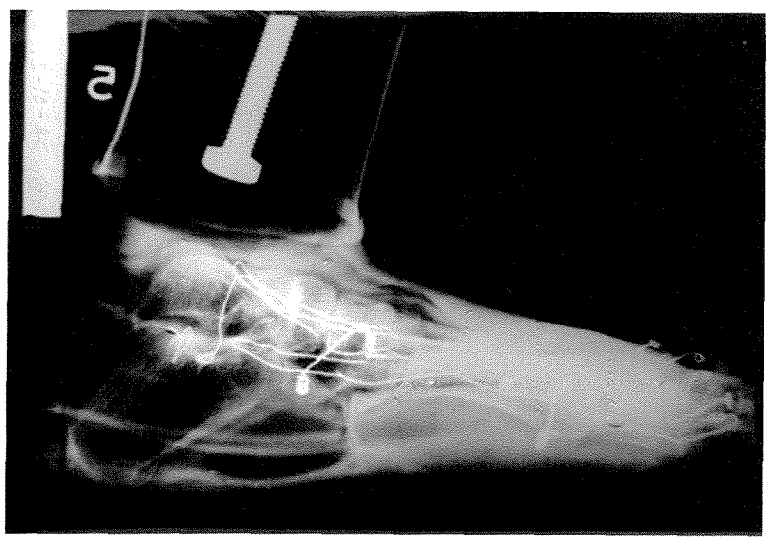


Figure 7a (left) and 7b (right).
(a) Design II. Fore-foot is loaded as sound limb is lifted. (b) Design III. Fore-foot is loaded as sound limb is lifted.



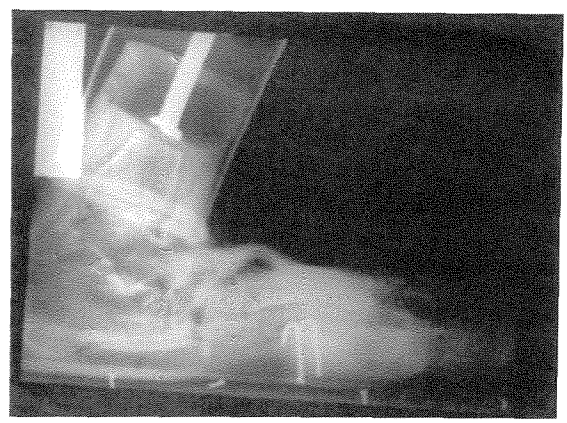


Figure 8a (left) and 8b (right).
(a) Design II. Lateral border of the foot is loaded against a wooden block placed under it. (b) Design III. Lateral border of the foot is loaded against a wooden block placed under it. The two bent nails show the thickness of the wooden block.

articulations perform their functions in a virtually normal manner.

The effect of continuous friction at the articulating surface when the prosthesis is used for periods longer than four weeks remains to be evaluated. If necessary, the bones could be coated to improve their function. Alternatively, synthetic bones of suitable lightweight, abrasion-resistant material could be used. Should the dried bones prove to be fatigue-resistant when used as endoskeleton in a prosthetic foot for a sustained period of time, this kind of foot could be planned for those who are to undergo an amputation, using their own amputated limb as a source for the ankle-foot prosthesis.

The shape and congruence of the articulating surface of the human foot bones provide independent movements in different planes and around different axes. Moreover, they have the inherent

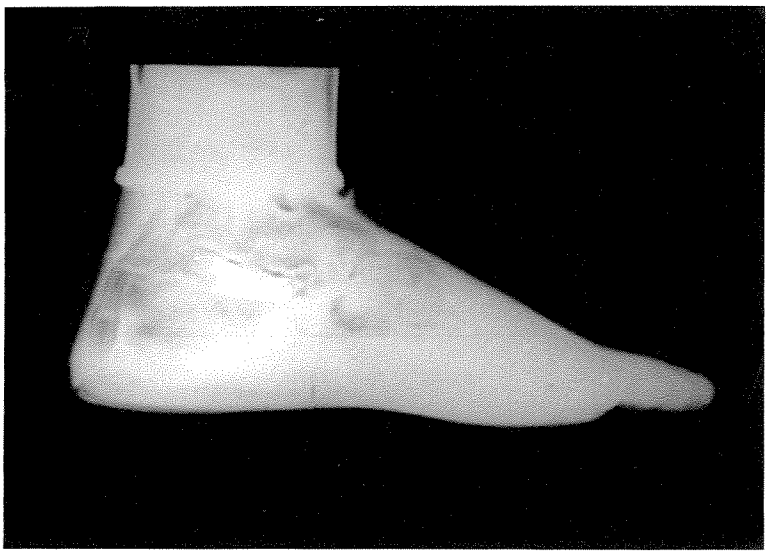


Figure 9.
Design III. Lateral radiograph taken after 4-week field test by subject. The bones are all intact and maintain their articulations.

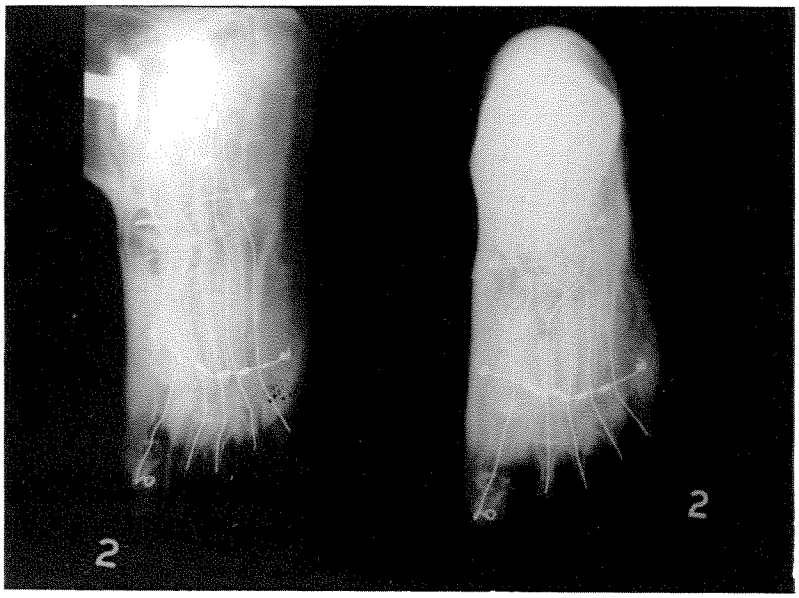


Figure 10.
Design II. Lateral and dorsoventral radiogram taken after 4-week field test by subject. The bones show multiple fractures and fragmentation.

property of locking the joints when the needed range of motion is reached in conformity with the requirements of the sequential stance phase stages of the gait cycle. They also are light in weight and provide nearly-normal joints.

The excellent flexibility of the conventional Jaipur foot enables wearers to walk barefoot on uneven, rough terrain and also to squat, sit cross-legged, and even to climb trees (3). The human-cadaveric-bone-endoskeleton foot reported on here retains all the qualities of the Jaipur foot, and provides for improved functional attributes. Its joint surfaces restrain movement after the optimum range is reached, and thus change the foot's flexibility (like the SAFE foot) to perform different functions during the stance phase. By allowing the sole of the artificial foot to conform to different terrains, impact forces between the socket and residual limb are greatly reduced. The present design is felt to closely simulate the musculoskeletal architecture of a normal human foot.

Journal of Rehabilitation Research and Development Vol. 27 No. 1 Winter 1990

REFERENCES

1. **James KB, Stein RB:** Improved ankle-foot system for above-knee amputees. *Am J Phys Med* 65(6): 301-314, 1986.
2. **Murphy EF:** Lower extremity components. In: *Orthopaedic Atlas, Vol. II.* Ann Arbor: J.W. Edwards, 148-161, 1960.
3. **Sethi PK, Udawat MP, Kasliwal SC, Chandra R:** Vulcanized rubber foot for lower limb amputees. *Prosthet Orthot Int* 2: 125-136, 1978.
4. **Wagner EM, Catranis JG:** New developments in lower extremity prosthesis. In: Klopsteg PE and Wilson PD (Eds.), *Human Limbs and Their Substitutes.* New York: McGraw-Hill, 481-513, 1954.