J. Biomechanics, Vol. 1, pp. 313-321. Pergamon Press. 1968. Printed in Great Britain

AN EXPERIMENTAL STUDY IN BIO-BALLISTICS: FEMORAL FRACTURES PRODUCED BY PROJECTILES – II SHAFT IMPACTS*

D. F. HUELKE, J. H. HARGER, L. J. BUEGE and H. G. DINGMAN
Department of Anatomy, The University of Michigan Medical School, Ann Arbor, Michigan

Abstract – To determine the response of human cortical bone to projectile impact, 364 projectile impact tests were conducted on the shafts of embalmed human femurs. Chrome steel spherical projectiles in two diameters, 0·250 and 0·406 in., were employed to differentiate the effects of projectiles of varied sizes and masses in impacts at the same velocity. It was found that the larger projectiles expended significantly more energy in fracturing a femur than the smaller projectiles did at an identical impact velocity. Also, when impacts in which larger and smaller spheres possessed identical kinetic energies were compared, it was found that the larger spheres still expended more energy in fracturing the femur. Finally, it was clearly demonstrated by these experiments that impacts to cortical bone of the femoral shaft by either size projectile caused greater energy expenditure than impacts to the distal end of the femur, which is composed almost entirely of cancellous bone.

IN A PREVIOUS article, we have reported the qualitative and quantitative effects of projectile impacts on human bone (Huelke *et al.*, 1968). Primarily the cancellous type of bone was subjected to impacts in that study, as the distal end of the femur was the target for the projectiles. Since the dense cortical type of bone is the other major component of the skeleton, the study was extended to determine the response of cortical bone to projectile impact.

MATERIALS AND METHODS

In this, the second phase of the study, embalmed human femurs were again used as the experimental specimens. A total of 219 femurs were subjected to impact by 0·250 in. chrome steel spheres at velocities from 200 ft/sec to 2200 ft/sec, and another 145 femurs were fractured by 0·406 in. chrome steel spheres at impact velocities from 200 ft/sec to 1550 ft/sec. The target area was the anterior surface of the femoral shaft at its midlength. At this level the femoral shaft is constructed as a marrow filled cylinder of dense cortical bone. Measurements of the diameter of the shaft were taken on each femur prior to its use, and the average outside diameter of the 364 specimens was 1·15 in. The thickness of the cortical bone wall of the shaft varies greatly among the specimens. It is markedly less in osteoporotic femurs than in radiographically normal specimens, and the wall thickness in mildly osteoporotic femurs is usually intermediate. To control for these variations in the structural condition of the bones, lateral and anteroposterior roentgenograms of each femur were evaluated by a radiologist. Each femur was categorized by radiographic criteria as normal, mildly osteoporotic, or osteoporotic (Fig. 1 and Table 1).

The experimental method employed in the study has been described (Huelke *et al.*, 1968). Briefly, it involves firing a 0·250 or 0·406 in. dia. steel sphere at the femur with a helium-operated gun. The velocity of the

---

* *Received* 28 *March* 1968.

Table 1. Sample sizes for ballistic impacts to embalmed human femurs

Projectile	Number of tests	
0·250 in. steel sphere	Shaft	Distal
Normal femurs	78	67
Mildly osteoporotic femurs	67	69
Osteoporotic femurs	74	84
Total	219	220
0·406 in. steel sphere		
Normal femurs	49	58
Mildly osteoporotic femurs	46	57
Osteoporotic femurs	50	58
Total	145	175

projectile before impact is measured electronically, and the exit velocity is determined from high-speed photographs of the event. From the computed kinetic energy of the sphere before and after impact, the energy expended by the projectile in fracturing the femur was calculated. A curve fitting program on an IBM 7090 computer was employed to determine the mathematical relation between impact velocity and the energy expended by the projectile in producing the fracture. A one-sided f-test was used to decide whether a quadratic or a linear relation best fitted each set of data. The individual paired values of data were, of course, scattered on both sides of the best curve, so a polynomial regression analysis was used to determine whether the different pairs of curves in the illustrations were statistically separate and distinct.

RESULTS

The curve which best fits the 219 paired values from shaft impacts by 0·250 in. spheres is a parabola described by the equation $y = -7{\cdot}833 + 0{\cdot}2661x + 0{\cdot}0012x^2$. The probability that chance alone is responsible for the parabola's fitting all 219 points better than the best linear equation is only one in one hundred ($p < 0{\cdot}01$). Statistically, therefore, we have a high level of confidence that the mathematical relation between impact velocity and energy loss in this case is parabolic. The curve best fitting the data for impacts by 0·250 in. spheres on the distal end of the femur is a parabola ($p < 0{\cdot}001$). Thus Fig. 2 shows that at a given impact velocity the 0·250 in. sphere expends much more energy when it fractures the femoral shaft than when it fractures the distal end of the femur. The magnitude of this difference is demonstrated in Fig. 3, for 0·250 in. projectile impacts to osteoporotic femoral shafts cause a greater energy loss than that expended in striking the less resistant distal end of normal femurs.

All six curves in Fig. 3 are parabolas. The curve best fitting the paired values for distal impacts to normal femurs is a parabola to a high degree of confidence ($p < 0{\cdot}01$), and the curves best fitting the data for distal impacts to osteoporotic and to mildly osteoporotic specimens were best fitted by parabolas to a significant level of confidence ($p < 0{\cdot}05$).

The difference between the curve for impacts by 0·250 in. spheres on the distal end of normal femurs and the curve for similar impacts on mildly osteoporotic femurs is quite significant ($p < 0{\cdot}01$). The difference between the curves for mildly osteoporotic bones and for osteoporotic specimens is not significant by polynomial regression analysis, i.e. the probability that the difference between the curves is due to chance alone is greater than five in a hundred.

The difference between curves for shaft impacts by 0·250 in. spheres on normal femurs and on mildly osteoporotic specimens is not statistically significant. The difference between the parabolas for shaft impacts to mildly osteoporotic bones and to osteoporotic bones is, however, quite significant ($p < 0{\cdot}01$).

The 173 paired values from distal impacts by 0·406 in. spheres were best fitted by a parabola ($p < 0{\cdot}001$). There was no significant difference, however, between the 'closeness of fit' of the best parabola and of the best straight line ($y = -32{\cdot}676 + 1{\cdot}2651x$) to the 137 paired values from shaft impacts by 0·406 in. spheres (Fig. 4). The correlation coefficient of the 137 data points with the parabola is 0·889 and with the straight line is 0·886, but

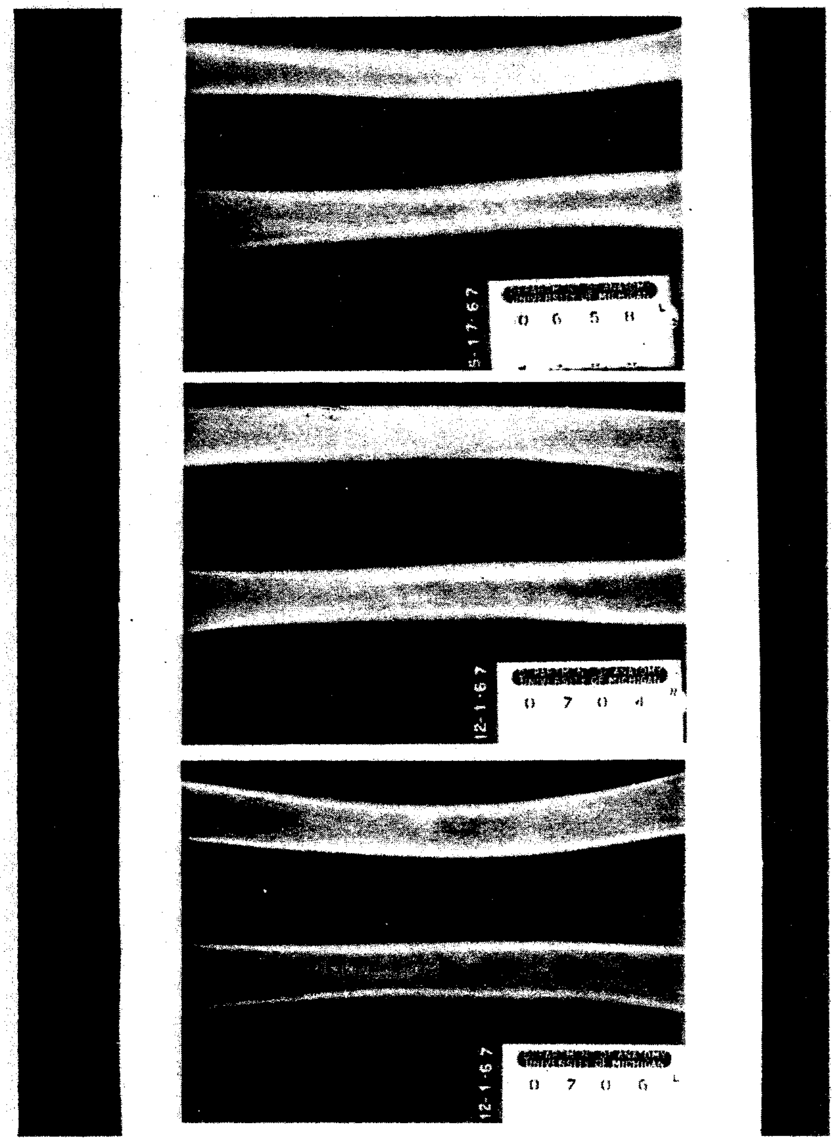

Fig. 1. Radiographic comparison of the physical condition of different specimens. The upper frame is a roentgenogram of a normal femur. Note the thickness and the density of the cortical bone in the walls of the shaft, indicating normally calcified bone tissue. Above is an anteroposterior view and below a lateral view. The middle frame is a roentgenogram of a mildly osteoporotic femur. The lowest frame is a roentgenogram of an osteoporotic femur. Note that the cortical bone in the walls is quite thin.

(*facing* p. 314)

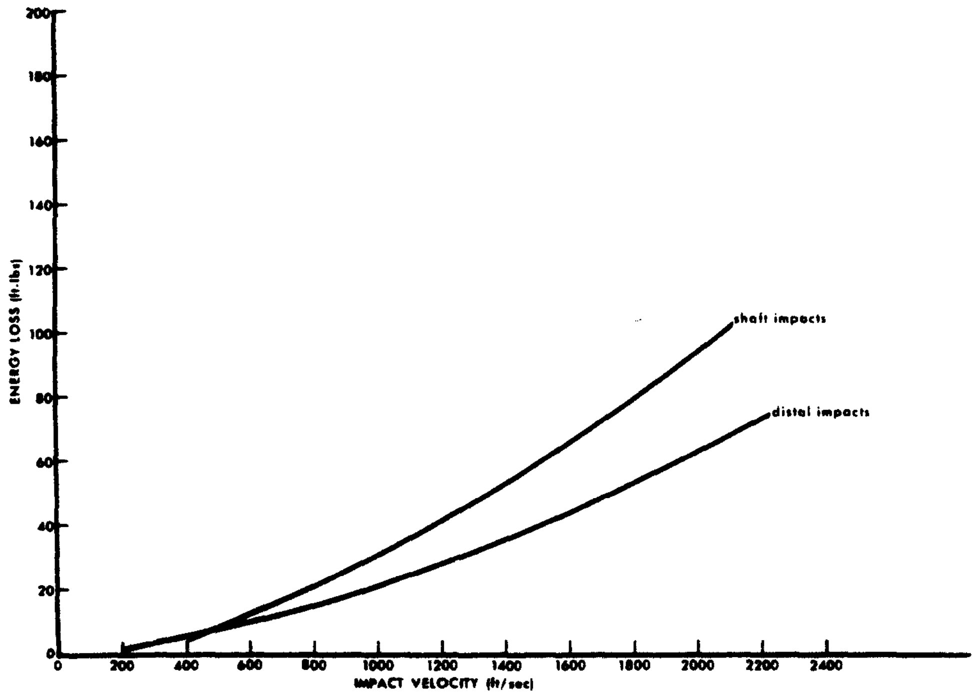

Fig. 2. The mathematical relation between impact velocity and energy loss in impacts by 0·250 in. steel spheres on embalmed human femurs.

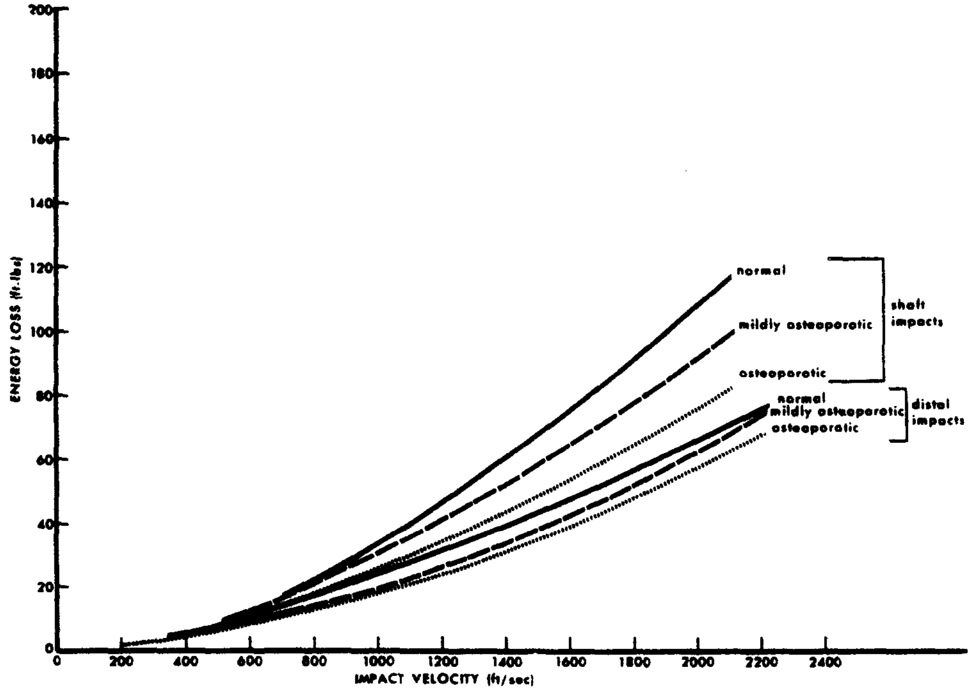

Fig. 3. The effect of the varied structural condition of the femurs on the magnitude of energy loss in impacts by 0·250 in. spheres.

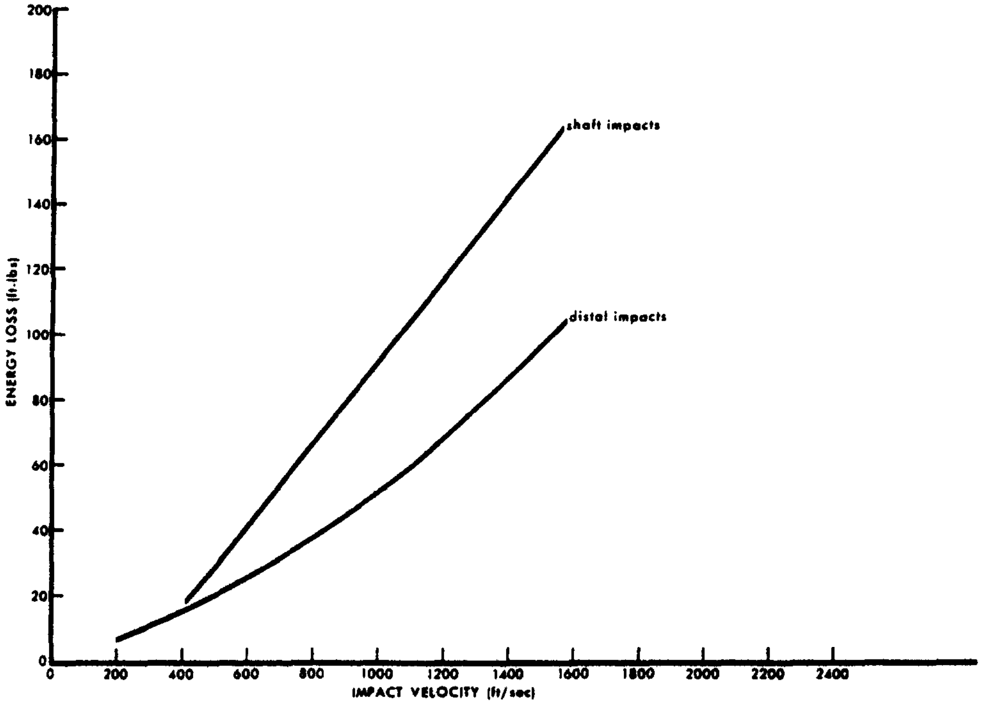

Fig. 4. The mathematical relation between impact velocity and energy loss in impacts by 0·406 in. steel spheres on embalmed human femurs.

according to the *f*-test this difference could be due to chance alone. Therefore, the mathematical relation between impact velocity and energy loss in shaft impacts by 0·406 in. spheres cannot statistically be proven parabolic.

It is clear from Fig. 4 that the 0·406 in. spheres expended much more energy in impacts with the femoral shaft than in distal impacts at the same impact velocity. This situation is very similar to that observed in impacts by 0·250 in. spheres. The difference in the magnitude of energy expended by the projectile in fracturing the two types of bone is readily apparent from Fig. 5: shaft impacts even to osteoporotic femurs cause a greater energy expenditure by the 0·406 in. spheres than distal impacts to normal specimens. It is also apparent, however, that the energy loss by 0·406 in. spheres at a given impact velocity depends on the structural condition of the femur as well as the target area. In either a distal or a shaft impact the 0·406 in. sphere expends more energy in fracturing a normal femur than a mildly osteoporotic bone; the same sphere would expend more energy fracturing a mildly osteoporotic femur than an osteoporotic specimen.

The three curves for distal impacts by 0·406 in. spheres are all quadratics. The curve for the normal femurs is a parabola to a significant level of confidence ($p < 0{\cdot}05$), while the curve best fitting the data from mildly osteoporotic bones is a parabola to a very high degree of confidence ($p < 0{\cdot}001$). The paired values for osteoporotic specimens are best fitted by a parabola to a high level of confidence ($p < 0{\cdot}01$).

In the cases of shaft impacts by 0·406 in. spheres to normal and to mildly osteoporotic femurs, the difference between the linear and quadratic curves was not significant. There-

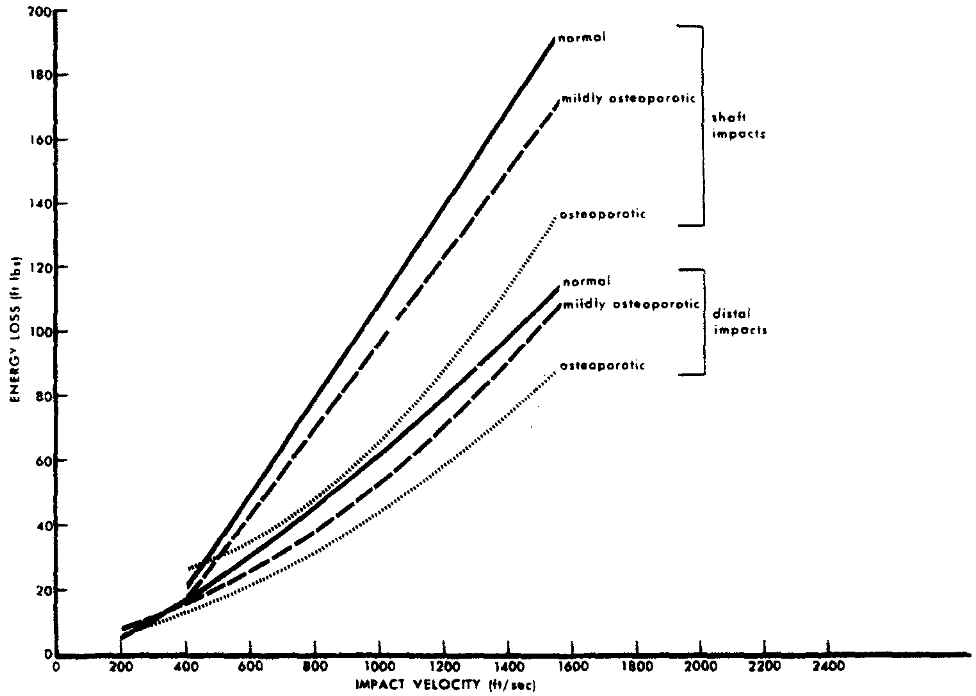

Fig. 5. The effect of the varied structural condition of the femurs on the magnitude of energy loss in impacts by 0·406 in. spheres.

fore, it must be concluded that the mathematical relation between impact velocity and energy loss is linear under these conditions. The data on shaft impacts to osteoporotic bones was best fitted by a parabola to a significant level of confidence ($p < 0{\cdot}05$).

By polynomial regression analysis, it was calculated that the difference between curves fitting the data from distal impacts by 0·406 in. spheres on normal and on mildly osteoporotic femurs was quite significant ($p < 0{\cdot}01$). The difference between the curves derived from distal impacts on mildly osteoporotic and on osteoporotic bones, however, was not significant.

In shaft impacts by 0·406 in. spheres, the difference between curves fitting the data on normal and on mildly osteoporotic specimens was significant ($p < 0{\cdot}05$). The difference between curves from mildly osteoporotic and from osteoporotic femurs was quite significant ($p < 0{\cdot}01$).

In shaft impacts as well as distal impacts, the energy expended by the projectile is greatly increased if the impact velocity of the projectile is held constant while its diameter and mass are both increased (Fig. 6). The mass of the 0·406 in. sphere (4·462 g) is 4·28 times that of the 0·250 in. sphere (1·043 g) and the striking (projected) area of the larger sphere (83·6 mm^2). Consequently, the energy expended by the 0·406 in. sphere is considerably greater in comparison to the 0·250 in. sphere. This difference is amplified in Fig. 7, for it is obvious that shaft impacts by 0·406 in. spheres even to osteoporotic femurs result in greater energy loss in fracturing the bone than shaft impacts to normal femurs by 0·250 in. spheres.

The qualitative aspect of impacts to the distal end of the femur by 0·250 and 0·406 in. spheres has been described previously (Huelke *et al.*, 1968). At low velocities the damage resulting from distal impacts is due to

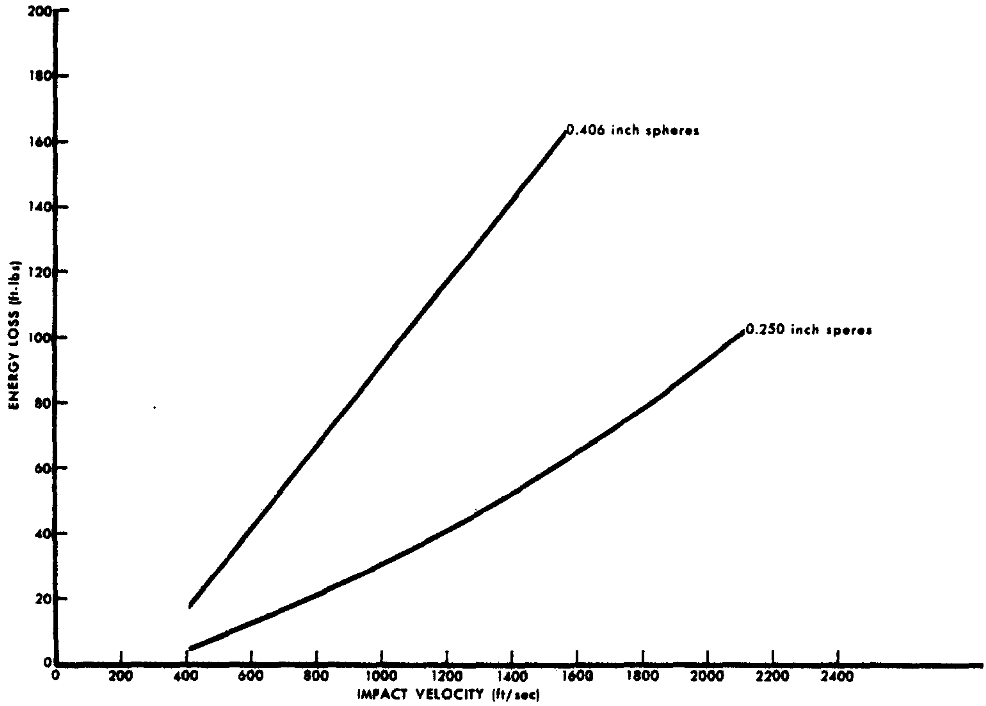

Fig. 6. The mathematical relation between impact velocity and energy loss in shaft impacts by steel spheres.

the mechanical effect of passage of the projectile through the bone, but at velocities in excess of 1000 ft/sec the damage produced is much more extensive due to the cavitation phenomenon. Though it is by no means certain that cavitation is the mechanism responsible for the increase, shaft impacts did produce increasingly severe damage at increasing impact velocities.

At an impact velocity of 400 ft/sec none of the five 0·250 in. spheres striking osteoporotic femoral shafts completely penetrated the shaft—they remained in the marrow cavity. At 500 ft/sec two of the four 0·250 in. spheres completely penetrated osteoporotic shafts, and at 700 ft/sec three of the four spheres did so. At an impact velocity of 800 ft/sec all four spheres striking osteoporotic femurs passed completely through the shaft.

In contrast, none of the four 0·250 in. spheres striking normal femurs at 700 ft/sec completely penetrated the shaft, and at 800 ft/sec only one of the six completely penetrated. At 1000 ft/sec, however, six of seven spheres completely penetrated the normal shafts, and all four spheres striking normal shafts at 1100 ft/sec did so.

Impacts at 400 ft/sec produced an exactly circular entrance hole of 0·250 in. dia. in the anterior wall of the shaft, though none of the spheres exited from the bone. Whatever the structural condition of the femur, at 500–700 ft/sec entrance holes were neatly circular, though with an occasional fracture line radiating from them. The exit holes in the area of the *linea aspera* (the heavy bony ridge on the posterior aspect of the femoral shaft) were roughly circular but were larger than the diameter of the sphere (Fig. 8). At impact velocities of 700 and 800 ft/sec the entrance and exit holes were enlarged and occasionally the shaft was completely broken, while at

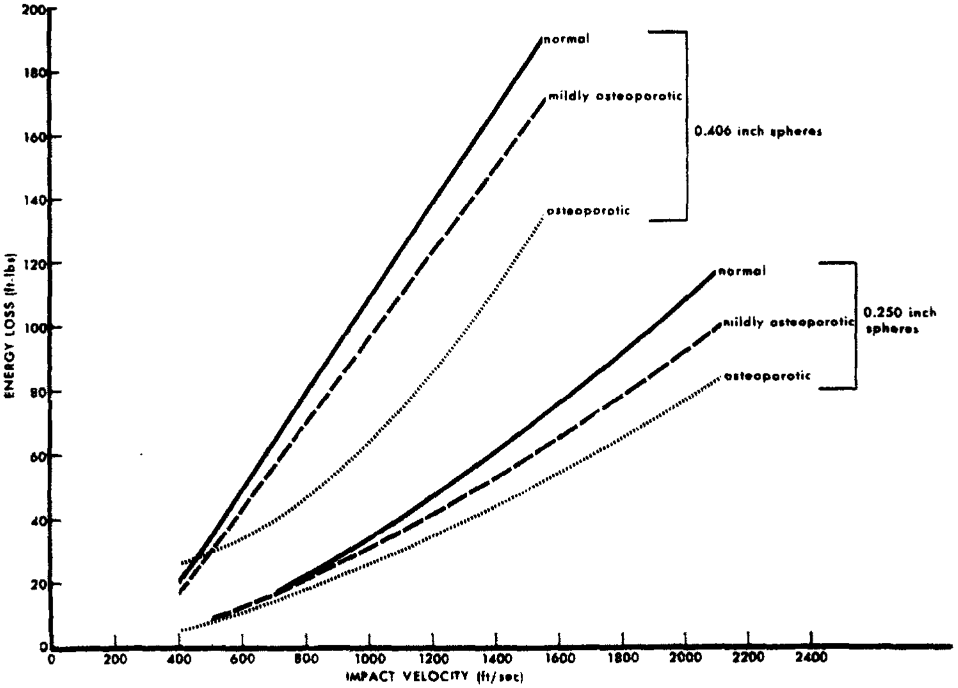

Fig. 7. The effect of the varied structural condition of the femurs on the magnitude of energy loss in shaft impacts by steel spheres. See text for explanation.

900 ft/sec and above most of the impacts produced a complete fracture and separation of the shaft (Fig. 9). At an impact velocity of 1000 ft/sec the damage consists of breaking the section of shaft on either side of the impact point into several fragments, thereby fracturing the bone in two. At impact velocities greater than 1000 ft/sec there is no essential change in the nature of the damage produced, only in how large a section of shaft is affected and how extensive the fragmentation (Fig. 10).

The damage produced by 0·406 in. spheres also increased rapidly to a maximum with increasing impact velocity, but at any given impact velocity the damage produced by the 0·406 in. projectile is considerably greater than that resulting from impact by a 0·250 in. sphere. At 200 ft/sec none of the four 0·406 in. spheres striking osteoporotic specimens completely penetrated the shaft (Fig. 11), but at 300 ft/sec three of the four did. At 400 ft/sec all four of the 0·406 in. spheres hitting osteoporotic bones completely penetrated the shaft.

In sharp contrast, none of the four 0·406 in. spheres hitting normal bones at 400 ft/sec completely penetrated the shaft—two remained in the marrow cavity and two rebounded out through the entrance hole. At 500 ft/sec, however, four of the five striking normal bones completely penetrated the shaft, and all four spheres completely penetrated the normal shaft at 600 ft/sec. The kinetic energy of a 0·406 in. sphere is 55·1 ft-lb at 600 ft/sec, whereas a 0·250 in. sphere must attain a velocity of 1248 ft/sec to possess the same amount of kinetic energy. Not until they attained an impact velocity of 1100 ft/sec did all four 0·250 in. spheres completely penetrate normal shafts.

With an impact velocity of 200 ft/sec the 0·406 in. spheres caused slightly enlarged entrance holes, and in two of the four cases the sphere hit the posterior wall of the shaft with enough force to break away a fragment of *linea aspera* (Fig. 12). Projectiles moving at 300 ft/sec caused some cortical bone fragmentation near the impact point (Fig. 13), and one broke the osteoporotic shaft in two. Even at impact velocites as low as 400–600 ft/sec the 0·406 in. spheres caused a marked degree of fragmentation about the impact point, and 73 per cent of the impacts produced complete fractures of the femoral shaft. Above 600 ft/sec very nearly all the impacts produced extensive destruction and fragmentation of the diaphyseal cortical bone about the impact point, resulting in complete fracture of the shaft (Fig. 14).

DISCUSSION

A previous experiment has proved that there is no significant quantitative difference between the response to projectile impact of the distal end of embalmed human femurs and fresh, unembalmed human femurs (Huelke *et al.*, 1968). This result strongly suggests that embalmed bones may provide an excellent experimental model for the response of human bones to projectile impacts *in vivo*.

The comparisons made in this paper permit three important conclusions to be drawn. First, projectile impacts to the femoral shaft result in much greater energy loss by the projectile than do impacts to the distal end of the femur at the same impact velocity. This result is obtained whether the projectile is a 0·250 in. steel sphere or a 0·406 in. sphere. The most probable explanation lies in the relatively great structural strength of the femoral shaft. This strength arises from the construction of the shaft as a thick-walled cylinder buttressed posteriorly by the mass of bone in the *linea aspera*. This configuration effectively distributes the force applied by the projectile around the entire wall of the shaft, thus accounting for the magnitude of energy expended by the projectile in producing fractures of that structure. In contrast, distal impacts involve distribution of the force of impact over the thin, flat plates of cancellous bone and via the fluid within the marrow spaces of cancellous bone. It has been shown that a cavitation phenomenon of the fluid within the cancellous bone is largely responsible for the increasingly greater damage produced in distal impacts at velocities above 100 ft/sec (Huelke *et al.*, 1968).

Our second major conclusion, however, is that cavitation is of minor importance in causing damage to the femur in shaft impacts. Projectile impacts to the distal end of dried human femurs were drastically different from distal impacts to embalmed femurs in the amount of energy lost by the projectile and in the nature of the damage observed between the two types of specimens. When the results of shaft impacts to embalmed femurs were compared with unpublished results obtained with dried femurs, there were no such significant qualitative and quantitative differences. Further, there was no evidence from high speed films of shaft impacts that cavitation of fluid in the marrow cavity increased concomitantly with increased impact velocity or increasing bone damage. Finally, it is not necessary to invoke cavitation as an explanation of the damage produced by projectile impacts to femoral shafts as it was in the case of distal impacts, for the bone of the femoral shaft is contiguous throughout the target region and thus may itself transmit force sufficient to cause a fracture at some distance from the impact point. In distal impacts the conical permanent cavity with its damage to bone at some distance from the flight path of the projectile strongly suggested the action of some sort of 'secondary missiles,' eventually determined to be fluid cavitation. The plates of cancellous bone could hardly transmit the force of impact. This exclusion of cavitation as an important factor in shaft impacts is, therefore, not certain but is quite probable.

The third important conclusion to be drawn concerns the qualitative and quantitative effects of projectile diameter and mass on the target specimen. As pointed out previously, the 0·406 in. sphere has by virtue of its greater mass a much greater kinetic energy than the 0·250 in. sphere at the same velocity. It possesses, therefore, much more energy to expend. In addition, however, the 0·406 in. sphere may possess the means to expend that energy more rapidly since it presents to the target a surface area 2·64 times that of the 0·250 in. sphere. At the same impact velocity, then, if both spheres required the same length of time to pass through the target, the 0·406 in. sphere with its greater rate of energy expenditure would expend a greater amount of energy in fracturing the bone. It is not at all certain, however, that this is, indeed, the mechanism by which larger projectiles expend more energy in impacts. In order to clarify this question, impact experiments must be conducted in which one of these parameters – either projectile diameter or mass – is held constant while the other is varied. This third conclusion, that present evidence on the point is inconclusive, leads directly to the next experiment on the program and must await an answer.

Acknowledgements – This research was supported in part by USPHS Grant DE-00895 from the National Institute of Dental Research, National Institutes of Health, Bethesda, Maryland, and by USPHS Grant UI-00008 from the National Center for Urban and Industrial Health, Cincinnati, Ohio.

We are grateful to Dr. Anthony F. Lalli, Department of Radiology, for his invaluable diagnostic assistance.

REFERENCE

Huelke, D. F., Harger, J. H., Buege, L. J., Dingman, H. G. and Harger, D. R. (1968) An experimental study in bio-ballistics: femoral fractures produced by projectiles – I. Distal impacts. *J. Biomech.* 1, 97–105.