The incongruous hip joint: a loading study

N. Y. P. AFOKE, P. D. BYERS, AND W. C. HUTTON

From the Polytechnic of Central London, School of Engineering and Science, London W1

SUMMARY Hip incongruity was studied by load-displacement and casting methods. Twenty-five joints were loaded in 5 different positions of the walking cycle. Seventeen of them had a space at the apex in all positions, while 3 were congruent at low loads, and the remaining 5 had femoral heads smaller than their acetabula. No trends with age were apparent.

In earlier experiments on hip incongruity we made casts of the space between the femoral head and the acetabulum while the joint was articulated and loaded to simulate conditions during the walking cycle.¹ These experiments confirmed the presence of a space in some joints, although it was effaced under relatively light loads. However, our casting method was unable to reveal the actual decrease in joint space with increasing load. We therefore felt it relevant to devise another experiment so that we could continually monitor joint incongruity and then measure the load at which the 2 shapes became congruent.

This load has already been introduced as the 'transition load' by Greenwald and O'Connor² in a report on experiments whereby the hip was progressively loaded and the displacement of the head into the acetabulum was recorded. The resultant load displacement curve had an initial nonlinear region followed by a linear region (similar to curve A in Fig. 3). They read off the value of load at the intersection of the 2 regions and interpreted this to represent the transition load, i.e., the load required to produce complete congruency.

We checked the accuracy of this method by taking casts of the joint space at various positions along the load displacement curve and found the transition load to be underestimated, concluding that this was due to cartilage, joint, and apparatus deformation. However, the procedure used in that assessment led to the method for determining the transition load which we used here. Basically it consists of recording the load displacement curve before and after filling the joint space with methyl methacrylate and of determining the load at which the 2 curves become parallel.

Materials and methods

HIP JOINTS

Cadaveric joints were used in this work. When the method had been established, 25 hips obtained from routine necropsies on 25 subjects aged 29 to 93 years were tested. They were stored in sealed polyethylene bags at a temperature of minus 20°C. Before they were tested, the hips were thawed at room temperature, the excess soft tissue was removed, and the joint disarticulated. The specimens were kept hydrated at all times with Ringer's solution, either by immersion or by wrapping with moistened cloth.

APPARATUS

This consisted of a rig designed to simulate the orientations of the hip in vivo during the walking cycle (Fig. 1). Simulation was achieved by mounting the femoral head and neck on to an adjustable swivel which allowed rotation in both the horizontal and vertical planes; the acetabulum was fixed in its natural position. Load was applied to the joint through a hydraulic servocontrolled testing machine. The ilium and the femoral shaft had been cut across planes (A'–A' and A–A, Fig. 2) perpendicular to the resultant force acting on the joint in the coronal plane, and the angle at which it acted remained the same in that plane during flexion, standing, and extension.³ The slight angulation of the femoral shaft of 9° with the vertical⁴ was also taken into account. The cut parts of the joint components were mounted in cups with quick-setting dental cement, and, for extra grip, wood screws were also inserted in the femoral shaft and ilium. The swivel holding the femoral head was clamped on to the upper crosshead of the machine while the acetabulum rested on the ram surface. With the femoral head set to the required angle, the 2 components were brought together to produce the required load on the joint.

Accepted for publication 9 May 1983.

Correspondence to Professor W. C. Hutton, Polytechnic of Central London, School of Engineering and Science, 115 New Cavendish Street, London W1M 8JS.

Fig. 1 The apparatus used to position the hip and subsequently load it.

Fig. 2 Diagram showing the angles of the head and shaft of the femur and the cutting planes (A'-A' and A-A) perpendicular to the resultant force acting on the joint in the coronal plane.

DETERMINATION OF TRANSITION LOAD

A joint was articulated in the desired position and a small preload of 40 N was applied to ensure minimal cartilage contact. The joint was then loaded up to 3 times body weight and the load-compression (or stiffness) curve was plotted automatically on an X-Y

recorder. This procedure was repeated 3 times to test the reproducibility of the curves. This done, the initial setting of the machine was noted, and after the joint was disarticulated liquid Simplex was poured into the inverted acetabulum. The joint was then rearticulated and the machine was brought back to the original setting. After the Simplex had cured (about 30 minutes), a set of 3 stiffness curves with the cast in situ was obtained. The joint was then disarticulated and the location of the cast in the acetabulum was recorded before the cast was removed and weighed (care being taken to cut out that part of the cast which represented the fossa). Now with the cast removed the joint was rearticulated, and another set of 3 stiffness curves was obtained to see if there was any change in the cartilage due to dehydration or creep. Thus for each position of the joint 3 sets of 3 stiffness curves, from the same origin, were recorded.

The joint was then allowed to recover in Ringer's solution for about 20 minutes before it was tested in a different position.

All the hips were tested in 5 positions based on the walking cycle: 25° and 10° flexion, 0° neutral, and 10° 20° extension. These increments cover the range from heel strike through to toe-off.

INTERPRETATION OF THE CURVES

Each of the 3 sets of curves showed good reproducibility, and since the curves obtained after the cast was removed were the same as those obtained before the cast was made only the latter are shown. Thus 2 typical curves are shown in Fig. 3. Curve A represents the stiffness of bone, rig, and cartilage deformation together with the closing of the joint space. Curve B—i.e., that obtained with the cast in situ—represents the stiffness of bone, rig, and cartilage deformation only. As cured Simplex is 100 times stiffer than cartilage, deformation of the cast is negligible; therefore the difference between the 2 sets of stiffness curves is a measure of the intercartilage space. The difference between the 2 sets of curves increases until a maximum is reached. The load at which there is no further increase is the transition load and this can be read from the curves to within ± 20 N. To check this, casts were made in 7 specimens at loads which were at or near the transition load. This confirmed that the space had virtually disappeared at the transition load, and when the load was significantly less (i.e., about 200 N), then some of the space remained.

Now we are quite safe in subtracting the curves in the upper, linear region where the difference is the 'maximum vertical displacement' (MVD), which is a measure of incongruity. It is not an absolute measure of the maximum joint space, as the position of maximum joint space may not lie on the same axis as

Fig. 3 Two typical stiffness curves. A is without Simplex and B with Simplex. The hatched area shows the lower part of B superimposed on A and represents the decreasing joint space.

the load applied in the tests (this can produce an error of only up to 6%). However, we cannot subtract the curves in the lower nonlinear region, as there they represent entirely different stiffnesses. Without the Simplex the applied load produces an increasing area of cartilage contact, whereas with the Simplex there is complete contact over the cartilage of both components at all times.

Results

All the specimens were examined and cartilage lesions were recorded. None of them had any progressive lesion in the anterosuperior segment. Limited lesions were present in all the various stages of development,⁶ an observation which established that the joints were unexceptional. The opportunity precisely to correlate contact areas with the distribution of cartilage alteration of limited progressions was overlooked until brought to our attention. It was then not possible adequately to recover this lost ground for a definitive statement. In consequence it

seems wiser to leave this question for another study, and suffice it to say here that we do not expect to find a simple relationship.

The results are presented in Table 1, where the transition load, the maximum vertical displacement, and the weight of the cast taken at 40 N are given for 5 positions of each joint.

Seventeen of the joints had stiffness curves similar to those in Fig. 4a and 8 of the joints had curves similar to those in Fig. 4b. The former indicate a definite joint space (as was evidenced by the location and size of cast) with a transition load to close it. In the second group the stiffness curves with and without the Simplex were nearly the same with correspondingly low, or zero, values of the transition load. This indicates that the articular cartilage surfaces at these joints were nearly or actually in contact at low loads. The casts showed that in 3 the 2 surfaces were virtually congruent and that in 5 there were incongruent areas on the sides indicative of a femoral head smaller than the acetabulum (Fig. 5).

These observations are reflected in the cast weight. The three congruent joints had light casts in all 5 positions. The 5 joints with small heads had heavier casts with the exceptions of a few individual casts. The distribution of the cast weights of the 'normal joints' had a wide spread and a skew to the right. The cast weights of the 5 joints with small heads fell within

Fig. 4 Actual curves obtained for 2 different joints.

Table 1 *Detailed results of the weight of the casts, the mean vertical displacement, and the transition load for the 5 joint positions*

<i>Specimen no.</i>	<i>Age</i>	<i>Sex</i>	<i>Mass (kg)</i>	<i>Code</i>	<i>25° Flex</i>	<i>10° Flex</i>	<i>0° Neut</i>	<i>10° Ext</i>	<i>20° Ext</i>
P11	37	M	63	CW MVD TL	1.103 0.84 2.26	1.576 0.83 1.94	1.536 0.65 1.94	1.631 0.77 2.26	1.31 0.65 2.26
P12	59	M	64	CW MVD TL	1.61 0.96 1.91	1.15 0.68 2.23	1.11 0.68 2.23	0.86 0.57 1.91	0.86 0.54 1.91
P13	81	M	52	CW MVD TL	1.79 0.53 1.57	2.286 0.64 1.57	2.64 0.56 1.57	2.39 0.48 1.96	3.18 0.74 1.57
P14	79	M	50	CW MVD TL	0.59 0.46 1.63	0.66 0.44 1.63	0.73 0.50 1.22	0.66 0.47 1.22	0.46 0.33 1.63
*+P15	37	M	49	CW MVD TL	0.72 0.22 2.49	0.505 0.09 —	0.50 0.08 —	0.60 0.1 —	0.654 0.1 —
*+P16	74	M	78	CW MVD TL	1.29 0.58 1.83	0.84 0.12 —	0.80 0.06 —	0.99 0.08 —	1.08 0.08 —
P17	62	F	62	CW MVD TL	0.325 0.30 0.66	0.475 0.34 0.98	0.57 0.36 1.31	0.575 0.38 1.31	0.72 0.46 1.31
‡P18	77	F	54	CW MVD TL	0.61 0 —	0.67 0 —	0.60 0.18 —	0.60 0.24 —	0.615 0.1 —
P19	72	F	53	CW MVD TL	0.634 0.44 1.15	0.765 0.48 1.15	1.15 0.74 1.92	0.915 0.55 1.92	0.89 0.47 2.31
P20	80	F	41	CW MVD TL	2.176 1.18 2.48	1.567 0.83 2.48	1.12 0.53 2.48	1.055 0.50 2.48	1.10 0.48 2.98
P21	50	F	89	CW MVD TL	1.325 0.53 1.60	1.133 0.30 1.37	1.18 0.26 1.14	1.122 0.23 1.14	1.14 0.24 1.14
*P22	38	M	39	CW MVD TL	0.195 0 —	0.16 0.6 —	0.22 0.14 1.57	0.19 0.13 1.57	0.15 0.0 —
P23	53	M	66	CW MVD TL	0.494 0.32 1.24	0.60 0.43 1.54	0.49 0.30 1.54	0.58 0.34 1.54	0.68 0.44 1.85
P24	71	F	56	CW MVD TL	0.274 0.21 1.46	0.28 0.26 1.46	0.454 0.44 1.09	0.254 0.14 1.09	0.245 0.10 1.09
*+P25	78	M	46	CW MVD TL	0.60 0.26 2.22	0.565 0.08 —	0.60 0.08 —	0.66 0.14 1.77	0.97 0.09 0.66
*+P26	93	M	64	CW MVD TL	0.35 0.1 —	0.36 0.08 —	0.475 0.08 0.95	0.43 0.10 0.64	0.55 0.20 1.59

Table 1 *Cont.*

<i>Specimen no.</i>	<i>Age</i>	<i>Sex</i>	<i>Mass (kg)</i>	<i>Code</i>	<i>25° Flex</i>	<i>10° Flex</i>	<i>0° Neut</i>	<i>10° Ext</i>	<i>20° Ext</i>
P27	88	M	42	CW	0.844	0.72	0.89	0.83	0.775
				MVD	0.30	0.16	0.24	0.25	0.18
				TL	2.91	1.94	2.91	2.91	2.91
P28	70	F	79	CW	0.14	0.355	0.235	0.505	0.435
				MVD	0.20	0.36	0.36	0.52	0.52
				TL	1.03	1.29	1.29	1.29	1.29
P29	49	M	71	CW	0.61	0.605	0.37	0.50	0.90
				MVD	0.24	0.38	0.16	0.21	0.40
				TL	1.72	1.72	1.15	0.86	1.43
P30	39	F	44	CW	0.29	0.47	0.45	0.49	0.39
				MVD	0.14	0.34	0.32	0.32	0.28
				TL	0.46	1.85	1.39	1.39	0.93
P31	73	F	79	CW	0.52	0.41	0.60	0.43	0.54
				MVD	0.62	0.48	0.61	0.43	0.40
				TL	1.55	1.55	1.55	1.55	1.81
*P32	29	M	54	CW	0.43	0.28	0.245	0.20	0.21
				MVD	0.20	0.0	0.08	0.0	0.0
				TL	—	—	—	—	—
P33	58	M	53	CW	0.835	0.62	0.455	0.46	0.28
				MVD	0.40	0.30	0.24	0.19	0.16
				TL	1.91	1.53	1.53	1.15	—
P34	32	M	69	CW	1.49	1.15	0.68	0.603	0.631
				MVD	0.67	0.52	0.24	0.16	0.21
				TL	1.18	1.18	1.18	1.18	1.18
*P35	79	F	66	CW	0.33	0.20	0.18	0.10	0.23
				MVD	0.15	0.0	0.0	0.0	0.0
				TL	—	—	—	—	—

* These joints showing very little space.

† These joints with the femoral head smaller than the acetabulum.

CW=Casting Weight (grams). MVD=Mean vertical displacement (mm). TL=Transition load (times bodyweight).

the lower range of this distribution and they were not distinguishable. But what does distinguish both of these smaller groups from the larger (but not from each other) is the maximum vertical displacement, which was very small or zero in both.

There was often striking variation between individual cast weights within a joint. This is true also of the maximum vertical displacement and of the transition load.

There was no clear relationship between joint position and maximum vertical displacement, though in some specimens (P12, P16, P20, P21, P33, and P34) there was a gradual decrease in maximum vertical displacement, going from flexion to extension. This lack of relationship was also reflected in cast weight against joint position and transition load against joint position.

The values of transition load normalised against body weight varied from a maximum of 2.4 down to zero, with many values just above zero.

When the average maximum vertical displacement was plotted against age, no obvious decline in displacement with age was apparent. The 8 cases which were nearly congruent at low loads did segregate from the others, but again showed no trend with age (Fig. 6). But this lack of correlation with age must be treated with some reserve owing to the very small numbers.

Discussion

The advantages of our method were that we had only to take 5 casts of each joint and load it 9 times for each position. Thus the method was convenient and

quick, though it requires some interpretation. Clearly, rather than using this inferred method we would have obtained more definitive results if we had taken casts every 100 N or 200 N. However, we felt that using exothermic Simplex about 40 times for each joint would have raised questions as to cartilage damage (we selected Simplex from preliminary studies as the best casting material and out of this experience no gain could be envisaged from using another material in the current study).

As in our earlier experiments, we found a great deal of scatter in the results. They fail to corroborate the conclusions of Walmsley⁷ and Cathcart⁸ that the hip is most congruent in extension. We could observe this in only 6 of the 25 joints. Similarly we cannot support the contention of Bullough *et al.*⁹ that incongruity decreases with age, but our results are not sufficiently numerous to refute that hypothesis. Further, we cannot agree to a fixed transition load for full congruency as stated by Greenwald and O'Connor² at 0.5 times bodyweight.

What is interesting is that some joints (5 in our sample) had femoral heads smaller than their acetabula, and, as our finite element study has shown,⁵ this results in high stresses on the roof of the acetabulum. A very much larger study would be required to ascertain if this population is at greater risk of osteoarthritis than those with heads larger than the acetabulum, or indeed whether, in view of the variability demonstrated, some other feature puts an individual at risk. In any case the results suggest that the concept, unqualified, of a sphere in an arch is too simple a description of a hip joint.

This work was supported by a grant from the Arthritis and Rheumatism Council and the work formed part of A. Afoke's PhD studies.

Fig. 5 Maps of the casts in one case from each of the 3 kinds of joint space: group A, apical space; group B1, nearly congruent; group B2, head smaller than acetabulum. The location of the cast is represented by the shaded area in each of the 5 positions used. The average weight of the 5 casts for each case is an indicator of thickness and volume; individual cast weights for each specimen are given in Table 1.

Fig. 6 The squares represent those 8 cases where the joint was nearly congruent at low loads. The circles represent the other joints.

References

- 1 Afoke N Y P, Byers P D, Hutton W C. The incongruous hip joint. A casting study. *J Bone Joint Surg* 1980; **62B**: 511–4.
- 2 Greenwald A S, O'Connor J J. The transmission of load through the human hip joint. *J Biomech* 1971; **4**: 507–28.
- 3 Bombelli R. *Osteoarthritis of the hip*. New York: Springer, 1976.
- 4 Steindler A. *Kinesiology of the human body under normal pathological conditions*. Springfield: Thomas, 1955.
- 5 Afoke N Y P. A mechanical study of the human hip joint with particular reference to joint incongruity. PhD thesis. Polytechnic of Central London, 1982.
- 6 Byers P D, Contepomi C A, Furkas T A. A post mortem study of the hip joint. *Ann Rheum Dis* 1970; **29**: 15–31.
- 7 Walmsley T. The articular mechanism of diarthroses. *J Bone Joint Surg* 1928; **10**: 40–5.
- 8 Cathcart R F. The shape of the normal femoral head and results from clinical use of more normally shaped nonspherical hip replacement prosthesis. *J Bone Joint Surg* 1972; **54A**: 1559.
- 9 Bullough P, Goodfellow J, Greenwald A S, O'Connor J J. Incongruent surfaces in the human hip joint. *Nature* 1968; **217**: 1290.