Intracapsular and atmospheric pressure in the dynamics and stability of the hip

A biomechanical study

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A cadaver study was undertaken to evaluate (a) the relations between the rotation around the axis of the neck of the femur, intracapsular effusion, and intracapsular pressure; and (b) the importance of the atmospheric pressure in stabilizing the hip joint. The following conclusions were reached: (1) There is no increase in intracapsular pressure within the normal range of rotation ("flexion") around the axis of the neck of the femur. (2) Intracapsular fluid (e.g., blood, pus, synovial edema and/or free synovial fluid) decreases this pressureless range of rotation, a likely cause of pain and subsequently flexion contractures. (3) Joint stability is primarily maintained by the atmospheric pressure within the normal range of rotation. The joint capsule is tightened only in extreme extension or flexion and contibutes to stability only in these positions. (4) The traction force needed to overcome the stabilizing effect of the atmospheric pressure and thus subluxate the adult joint is approximately 200 N, in a child less, proportional to the square of the diameter of the femoral head. We also propose that intracapsular fluid makes the joint potentially unstable, a prerequisite for unfavorable mechanical cartilage load. These findings have clinical implications in synovitis, septic and juvenile arthritis, congenital dislocation of the hip, arthroplasty, and trauma.

The muscle forces around the hip, the joint capsule, the anatomic geometry of the femoral head and of the acetabular socket are usually mentioned as the stabilizing factors in the hip joint, e.g., in relation to congenital dislocation of the hip, dysplasia due to neurologic defects, or dislocations following hip joint replacements. Recently, interest has been focused on the importance of an increase in intracapsular pressure in relation to the blood supply to the head of the femur in the child, as well as in the adult (Lucht et al. 1983, Kloiber et al. 1983, Minikel et al. 1983, Sty et al. 1983, Wingstrand et al. 1985b, Rydholm et al. 1986, Wingstrand et al. 1986, Wingstrand and Sundén 1987, Pettersson et al. 1989). Our purpose was to clarify biomechanically the role of the intracapsular pressure in joint dynamics and of the atmospheric pressure in relation to the capsule in stabilizing the hip joint and the impact of these mechanisms in hip-joint disease.

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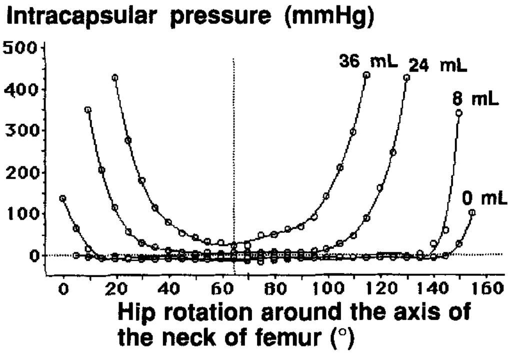
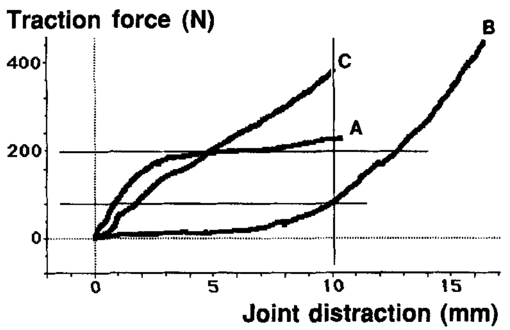
Material and methods

Six cadaver hips (patients age ranging from 19 to 77 years) where dissected and prepared with an intact joint capsule, including a sufficient part of the pelvis and 15 cm of the proximal part of the femur.

The specimens were firmly mounted with bolts securing the pelvis in a specially designed test rig. A 2-mm steel axis allowing rotation around the axis of the neck of femur was firmly attached to the major trochanter region. The mounting allowed for the following parameters to be controlled and simultane-





Cadaver hip specimens mounted in a test rig where joint distraction, traction force along and rotation ("flexion") around the axis of the neck of femur, as well as intracapsular pressure and volume of intracapsularly infused saline, were simultaneously monitored.

Figure 1. The intracapsular pressure in relation to rotation around the axis of the neck of the femur and increasing intracapsular volumes of infused saline. The hip is in maximum extension at 0°. The normal pressureless range of rotation decreases as the volume of intracapsular fluid increases.

Figure 2. The traction force needed to distract (subluxate) the joint. A) Joint capsule intact, hip in medium rotation around the axis of the neck of the femur. B) Joint capsule opened via small longitudinal incision to neutralize atmospheric pressure, hip in medium rotation around the axis of the neck of the femur. C) Joint capsule opened, hip in full extension.

ously monitored; joint distraction, i.e., translation (mm), along the axis of the neck of the femur was recorded via a strain-gauge transducer, as was traction force (N) along along the axis of the neck of the femur. Intracapsular pressure (kPa) was recorded via a 0.8-mm intracapsular cannula introduced tangentially through the iliofemoral ligament directed to the midpart of the neck of the femur. A nonvolume-consuming piezoelectric pressure transducer was connected by a saline-filled pressure-resistant tube for continuous pressure recording. The volume (mL) of intracapsularly infused saline was controlled by the stepwise infusion of 0–36 mL in 4 mL steps by a three-way stopcock. Rotation (°) around the axis of the neck of the femur was controlled by a scale. Three hips were used to study the relationship between rotation and intracapsular pressure and volume, whereas the remaining three were used to study the role of the atmospheric pressure in relation to the capsule in stabilizing the joint. The specimens were heated to approximately body temperature before starting the experiments. The formula $F = (\pi * D^2/4) * (P_a - P_v) * 10^2$ was used to calculate the theoretical traction force necessary to distract, i.e., subluxate, the hip joint. F = traction force in newton, D = diameter of the head of the femur (m), P_a = atmospheric pressure (mBar), P_v = vapor pressure in the joint (mBar) at body temperature.

Results

The findings in both series in the specimens studied were concordant. The actual recordings from two hip specimens (Figure 1 and 2, respectively) are used to illustrate the results:

1. Results regarding the relationship between rotation, i.e., "flexion" around the axis of the neck of the femur, the intracapsular pressure, and the volume of intracapsular fluid

In the "normal" hip, i.e., without any infusion of intracapsular saline, there was no increase in intracapsular pressure within the normal range of rotation around the axis of the neck of the femur (Figure 1). Only in the positions of extreme rotations was there an increase in intracapsular pressure. Following the stepwise infusion of saline, this pressureless range of rotation decreased and finally ceased as the pressure was significantly increased even in the position of midrotation (Figure 1).

2. Results regarding the relationship between traction force along the axis of the neck of the femur in relation to hip-joint distraction with and without the effect of the atmospheric pressure

With the hip in medium rotation around the axis of the neck of the femur and with the joint capsule intact (Figure 2 A), there was an increase in traction force in this specimen as the hip was distracted up to around 3 mm from which point a constant traction force of ≈ 200 N was needed to distract the joint another 5 mm, thus representing the force necessary to overcome the stabilizing effect of the atmospheric pressure. This correlated very well with the theoretically traction force value calculated from the above formula.

Following the elimination of the effect of the atmospheric pressure by opening the joint capsule, still with the hip in medium rotation around the axis of the neck of the femur (Figure 2 B), the joint can be subluxated about 8 mm without any significant traction force until the joint capsule is tightened and resists further distraction.

In Figure 2 C the joint was rotated into maximum extension and the capsule is open. In this position the capsule is tightened and resists distraction immediately. A traction force of ≈ 400 N is needed to distract the joint 10 mm, approximately five times more than in medium rotation as in Figure 2 B and approximately twice as much as in Figure 2 A, where the atmospheric pressure was in effect.

Discussion

The following conclusions, in accordance with basic laws of pressure, can be drawn: 1. In the normal joint there is no increase in the intracapsular pressure within the normal range of rotation around the axis of the neck of the femur, only in the extreme rotatory positions. 2. Intracapsular fluid (e.g., blood, pus, synovial oedema and/or free synovial fluid) decreases this pressureless range of motion, a likely cause of pain and subsequently flexion contractures. 3. Within the normal range of rotation, stability is primarily (not taken into consideration muscular tone) maintained by the atmospheric pressure. As pointed out by Walmsley (1928), the joint capsule is tightened only in the extreme end-rotatory positions around the axis of the neck of the femur corresponding to flexion or extension. 4. The traction force needed to distract or subluxate the adult joint is theoretically and in these specimens approximately 200 N (Figure 1). In a child, it is less, proportional to the square of the diameter of the femoral head.

The vascular supply to the epiphysis and proximal part of the growth plate in the child is met via intracapsular branches emanating from the medial femoral circumflex artery (Trueta 1957, Ogden 1974). Any increase in intracapsular pressure above the level of the pressure in the veins will decrease the pressure gradiant across the capillary bed up to a point where the metabolic demands of the epihyseal cells are no longer met (Madsén 1980). Such a mechanism has been demonstrated experimentally (Kemp 1981, Lucht et al. 1983) and clinically in transient synovitis of the hip (Kloiber et al. 1983, Wingstrand 1985a, b, Wingstrand 1986), as well as in septic arthritis (Wingstrand et al. 1987), and in juvenil chronic arthritis of the hip (Rydholm et al. 1986).

Isotope studies in transient synovitis and septic arthritis have revealed an absence of isotope uptake in the epiphysis in the acute phase of the disease (Kloiber et al. 1983, Sty 1983, Minikel et al. 1983, Hasegawa 1985, Wingstrand et al. 1985a, b, 1987, Hasegawa et al. 1988). This epiphyseal ischemia is correlated with an increase in intracapsular pressure and was shown to be reversible, either spontaneously, most likely due to intermittent decompression by flexion of the hip, or following decompression by joint aspiration (Kloiber 1983, Wingstrand et al. 1985b).

Avascular necrosis of the epiphysis in the hip was a common finding in hemophilic children following hip joint tamponade (Ahlberg 1965). This complication has virtually disappeared with the introduction of specific treatment in these children (Pettersson et al. 1989), which supports the assumption of the hip joint tamponade with compromised blood flow as a possible mechanism.

The incidence of avascular necrosis of the epiphyses in children with congenital dislocation of the hip varies widely in the literature and varies depending on the regime of treatment (Crego et al. 1948, Pool et al. 1986). Westin et al. (1976) and Gregosiewicz and Wosko (1988) demonstrated a close correlation between treatment with immobilization in flexion/abduction, i.e., the "frog-leg" position and subsequent avascular necrosis of the epiphyses. As shown in our study and clinically in children with congenital dislocation of the hip (Wingstrand and Sundén 1987), the position of flexion/abduction, i.e., maximum rotation around the axis of the neck of the femur, produces a hazardous increase in the intracapsular pressure. This is a probable cause of the avascular necrosis that also occurs in the nonsymptomatic contralateral hip immobilized in the same position. (Westin et al. 1976).

In undisplaced fractures of the neck of the femur, the head is again, as in childhood, solely dependent on intracapsular branches for its vascular supply. These fractures have been shown to produce a hip joint tamponade with intracapsular pressures well above hazardous levels; and isotope studies have revealed reversible transient ischemia of the head of the femur (Wingstrand et al. 1986).

The "pressureless" range of motion will decrease with any increase in the intracapsular volume of fluid either due to bleeding following trauma or septic or aseptic synovitis. The less painful position, spontaneously adopted by these patients is in medium flexion and slight abduction, i.e., in midrotation around the axis of the neck of the femur, which is the postion of minimum intracapsular pressure (Figure 1). Subsequently, this is probably the primary cause of the flexion contracture developed by patients with chronic synovitis, for instance, children with juvenile chronic arthritis (Rydholm et al 1986). Pain-transmitting nerves have been identified in synovial membranes (Kellgren and Samuel 1950, Grönblad et al 1985).

As shown in our present study, the atmospheric pressure is primarily responsible for stabilizing the hip joint within the normal range of rotation around the axis of the neck of the femur. The hip-joint capsule does not contribute to stability except in the positions of extreme rotation around this axis. Not taken into consideration, the muscle tone, or in patients were muscle tone is absent, the traction force necessary to overcome the effect of the atmospheric pressure and thus distracting, or subluxating, the joint in the adult is approximately 200 N. This force is proportional to the square of the diameter of the femoral head. Thus, in the child less traction force is needed to dislocate the joint, which could be one factor to explain why young children suffer traumatic dislocation following milder trauma (Barquet 1982).

An optimal distribution of the load forces across the joint cartilage depends on an accurate fit in the articulation. Any disturbance in this congruency results in an unfavorable rapid increase in cartilage load (Brown et al. 1978, 1983, Rapperport et al. 1985). Normally, there is no, or very little, free joint fluid, but under pathologic conditions, such as synovitis or trauma with free intraarticular fluid, the stabilizing effect of the atmospheric pressure is counteracted, because this fluid may partially replace the volume of the head of the femur in the acetabulum. This may result in microinstability with unfavorable mechanical cartilage load in combination with the cartilage edema (Egund et al. 1986) and cartilage degradation (Lohmander et al. 1987) demonstrated in transient synovitis of the hip and in Legg-Calvé-Perthes' disease. Experimentally induced synovitis has been shown to cause cartilage edema and degradation of the mechanical properties (Gerschuni et al. 1981, 1984). These observations and the subsequent unfavorable cartilage load due to instability in the head-acetabulum fit could explain the anterolateral subchondral fracture observed in the early stage of Legg Calvé-Perthes' disease.

Dislocation following hip joint arthroplasty occurs in approximately 4 percent usually in the early postoperative stage (Lindberg et al. 1982, Kristiansen et al. 1985). Because the joint components are then surrounded by fluid, the stabilizing effect of the atmospheric pressure is eliminated. After the resorption of the postoperative bleeding, the prerequisite for the stabilizing effect of the atmospheric pressure is established.

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