

BIOMECHANICS OF HIP DYSPLASIA

P. MAQUET

When walking, each hip alternately carries the body mass minus the supporting leg. This mass exerts a force K acting on the hip with a lever arm h' ; it is counterbalanced by a force M exerted by the abductor muscles, which acts on the hip with a lever arm h . The hip joint transmits the resultant R of forces K and M . Force R evokes compressive stresses in the joint. In a normal hip, force R is exerted at the center of the force transmitting surface of the joint, and the stresses are evenly distributed over this surface. This is reflected by the narrow ribbon of subchondral sclerosis in the roof of the socket. The normal femoral neck is stressed in bending with shear. It has a medial bundle of cancellous trabeculae, stressed in compression, intersecting with a lateral bundle, stressed in tension. Dysplasia and an imbalance of the muscles may have similar mechanical consequences: a shortening of the lever arm h and a more vertical orientation of force M . Shortening of h results in an increase of the force M necessary to counterbalance the moment of force K ; the change in direction of force M displaces the resultant R towards the edge of the socket. The result is an increased resultant force R which becomes unevenly distributed over a smaller surface. Subluxation of the femoral head due to a shallow socket will also result in an uneven distribution of force R on a smaller surface. The abnormal distribution of compressive stresses is reflected by the development of a triangular sclerosis at the edge of the socket. This is the beginning of subluxating osteoarthritis of the hip. In a coxa valga the femoral neck may be stressed in a pure compression. This appears in the structure of the cancellous bone of the neck. Coxa vara has opposite consequences: lengthening of the lever arm h of the abductor muscles and a more horizontal orientation of force M . This results in a decrease of the resultant force R , which is displaced medially over a larger surface, resulting into smaller compressive stresses in the joint. If the acetabular cartilage of the socket does not develop further

medially, the distribution of compressive stresses may become uneven with a maximum medially, where a dense triangular sclerosis develops. This is the beginning of protrusive osteoarthritis of the hip. In coxa vara, the femoral neck is stressed in bending more than in a normal hip, which is reflected by more marked cancellous trabeculae which intersect at right angles in the femoral head. The medial bundle is stressed in compression, the lateral bundle in tension.

Keywords : hip ; dysplasia ; osteoarthritis ; biomechanics.

Mots-clés : hanche ; dysplasie ; arthrose ; biomécanique.

Pauwels analyzed tridimensionally the forces exerted on the hip and drew therapeutic applications from his analysis. Our experience confirms his theory.

NORMAL HIP

During walking each hip alternately carries the mass of the body minus the supporting leg (fig. 1). This mass acts through its weight (81% of total body weight) and a force of inertia due to its accelerations and decelerations, exerting on the hip a force K . Force K acts eccentrically on the joint with a lever arm h' (about 12 cm) and is balanced by a force M developed by the abductor muscles. Force M acts with a lever arm h (about 4 cm) in such a way that $M.h = K.h'$. The hip transmits the resultant or vectorial sum R of forces

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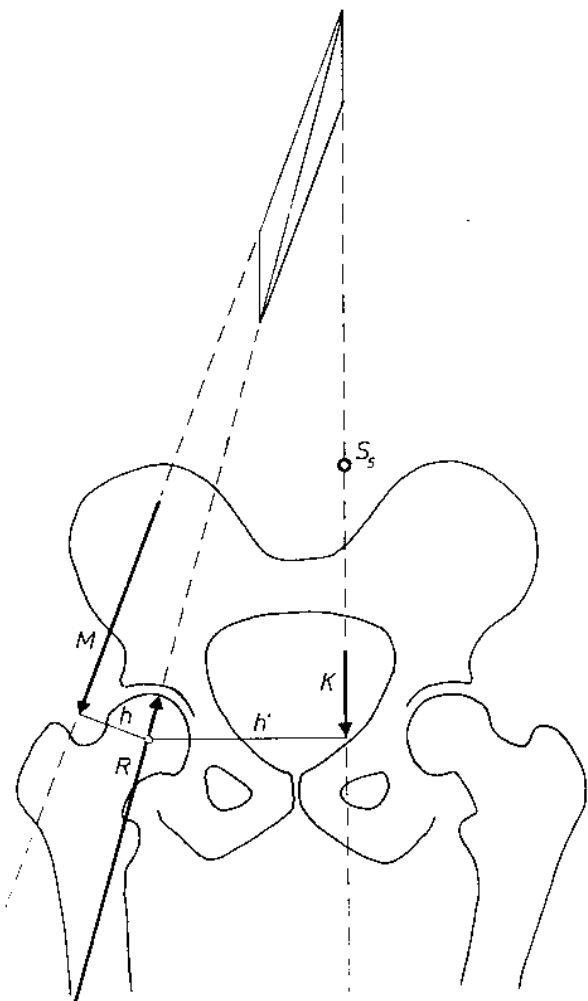


Fig. 1. — Forces exerted on a loaded hip. S_5 centre of gravity of the mass of the body supported by the hip; K force exerted by the mass of the body supported by the joint; h' lever arm of K ; M force exerted by the abductor muscles; h lever arm of M ; R force transmitted across the joint (= resultant of forces K and M).

K and M . Force R goes up to more than 4 times body weight during normal walking. This force evokes compressive stresses in the joint. In a normal hip, these compressive stresses are evenly distributed over the force transmitting surface of the joint. Pauwels has shown that the quantity of bone depends on the magnitude of the stresses. This explains why the subchondral sclerosis appears as a thin ribbon of dense bone in the roof of the socket (fig. 2). This ribbon of even width throughout indicates an even distribution of the



Fig. 2. — The subchondral sclerosis (sourcil) corresponds to the distribution of the compressive stresses in the joint. The ogives formed by the bundles of medial (compressive) and lateral (tensile) trabeculae indicate that the femoral neck is stressed in bending, with shear, by a compressive force acting obliquely in relation to the axis of the neck.

compressive stresses (or articular pressure) in the joint.

The resultant force R acts medially to the axis of the femoral neck and this more and more from the centre of the femoral head to the basis of the neck. Force R stresses the femoral neck in bending (fig. 3a) so that compressive stresses arise in the medial aspect of the neck, tensile stresses in its lateral aspect. The trabeculae of cancellous bone in the neck correspond to the trajectories of these stresses (fig. 2). They form ogives typical of bending stressing with shear through a compressive force acting obliquely in relation to the axis of the neck.

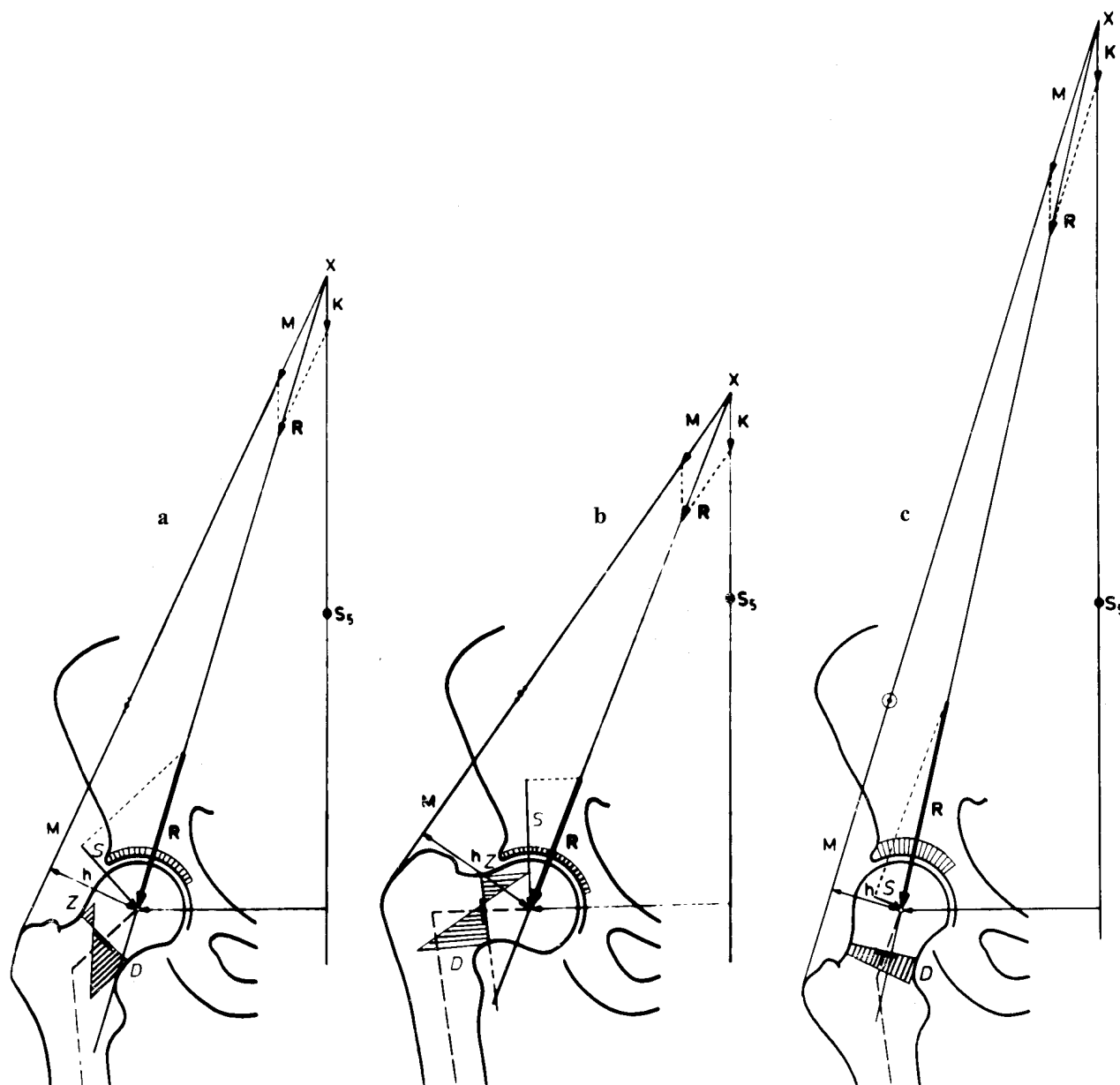
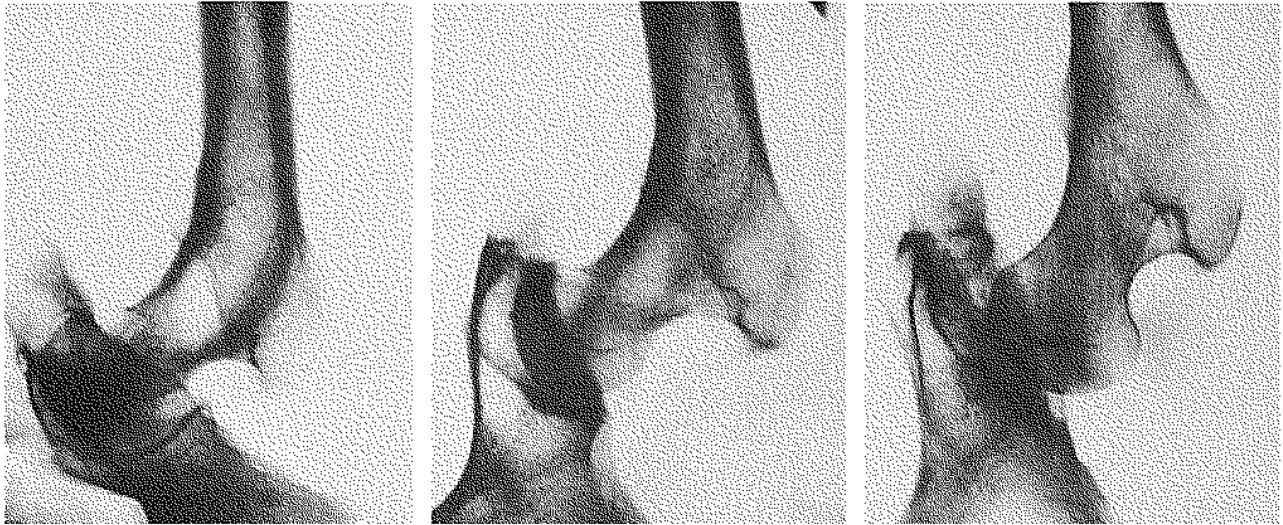


Fig. 3. — Same signs as in Fig. 1. *S* shear; *D* compression; *Z* tension. The core of the neck is indicated by a black line. *a* normal hip; *b* coxa vara; *c* coxa valga (Maquet, 1985; after Pauwels, 1973).

SUBLUXATING DYSPLASIA

In a coxa valga (fig. 3c), the lever arm *h* of the abductor muscles *M* is shorter than in a normal hip (fig. 3a). The muscles, therefore, must develop more force to balance the force *K* due to the body mass. Moreover, their line of action is closer to

the vertical. This results in a closing of the angle formed by the lines of action of forces *K* and *M*. Closing of this angle and increase of force *M* both contribute to an increase of the resultant *R*. Moreover, the line of action of force *R* is brought closer to the edge of the socket. This decreases the weight bearing surface of the joint. Diminution



a

b

c

Fig. 4. — a coxa valga ; b normal hip ; c coxa vara (Maquet, 1985).

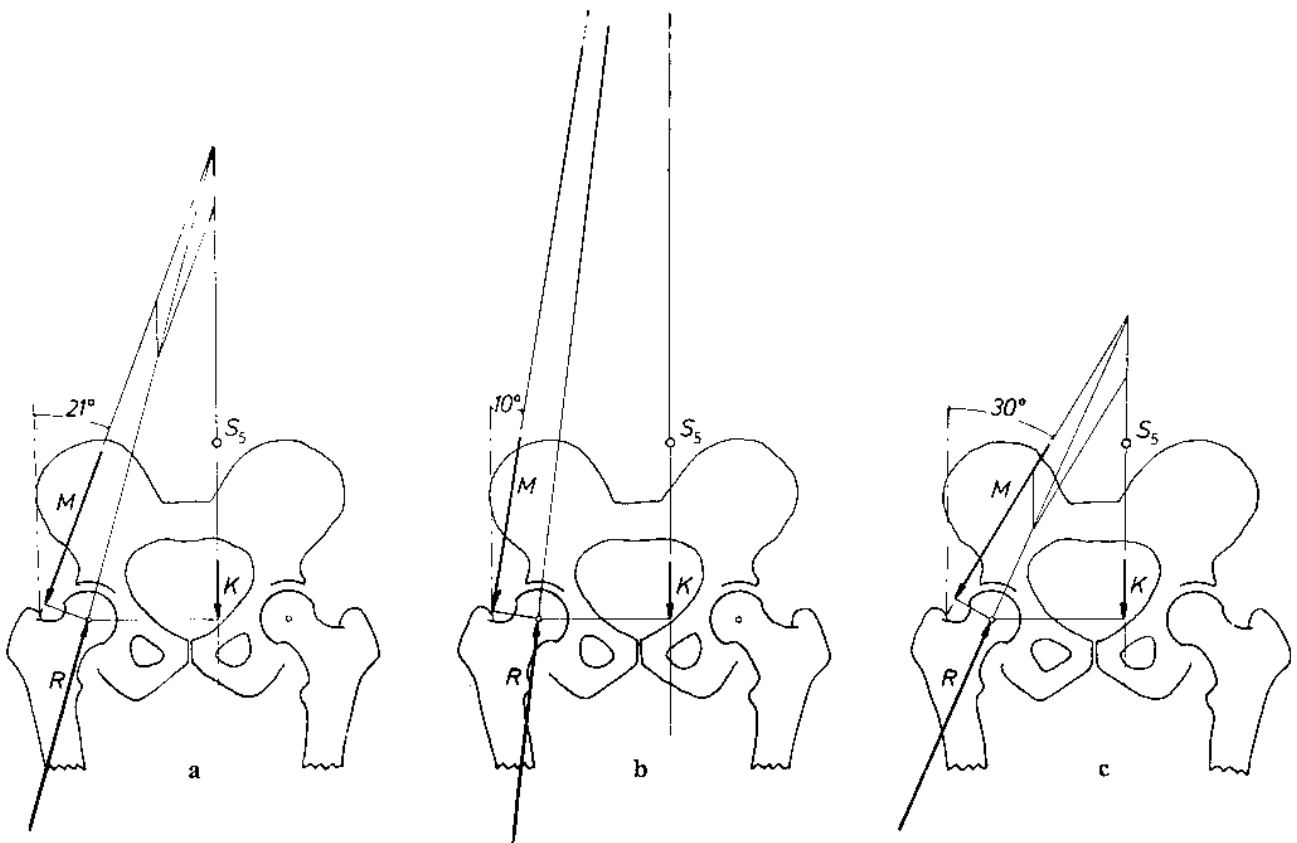


Fig. 5. — a The line of action of the resultant of the muscular forces has been calculated as forming an angle of 21° with the vertical (Pauwels).
 b If the longitudinal pull prevails and the line of action of the muscular force is closer to the vertical, the resultant R is brought closer to the edge of the socket.
 c If the transverse pull prevails and the line of action of the muscular force is further away from the vertical, the resultant R is displaced medially towards the depth of the socket.

of the weight bearing surface of the joint and increase of the force R transmitted across the joint both increase the articular compressive stresses.

On the other hand, in a coxa valga, the resultant R acts in the core, i.e. the central part, of the femoral neck, close to the axis of the neck. Consequently, in this instance, the femoral neck is stressed in pure compression (fig. 3c). The ogives of the normal hip are replaced by longitudinal trabeculae which fill up all the femoral neck (fig. 4a).

If the hip is subluxated through insufficiency of the acetabulum, the distribution of the articular compressive stresses is no longer symmetrical on both sides of the line of action of force R . Their diagram is triangular with a maximum at the edge

of the socket. The more pronounced the subluxation, the higher the dense triangle corresponding to the stress diagram.

In a hip the skeletal elements of which are normal, predominance of the vertical pull of the abductor muscles brings force M closer to the vertical (fig. 5b) than in a normal hip (fig. 5a). This increases the resultant force R by closing the angle formed by the forces K and M , and moves this force R closer to the edge of the socket. The consequence is a diminution of the weight bearing surface of the joint. Increase of force R and decrease of the articular weight bearing surface combine to increase joint pressure. This explains that, in the same patient with two apparently similar hips (fig. 6), one develops osteoarthritis

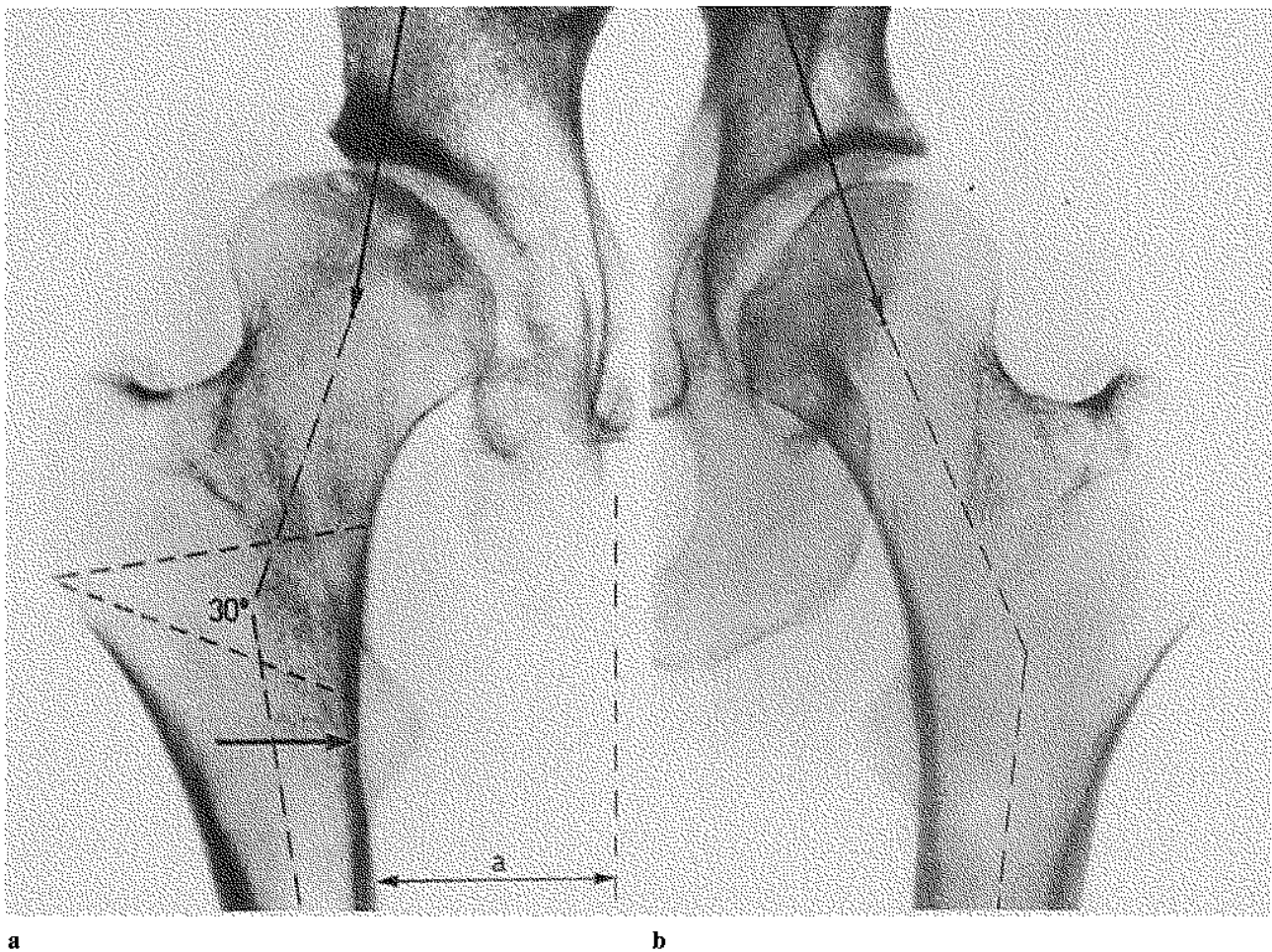


Fig. 6. — The two hips of the same patient. Their contours can be superimposed: they are identical. One presents with a normal subchondral sclerosis (b). A dense triangle at the edge of the socket in the other (a) demonstrates that the resultant force R acts closer to the edge of the socket (Pauwels, 1973).

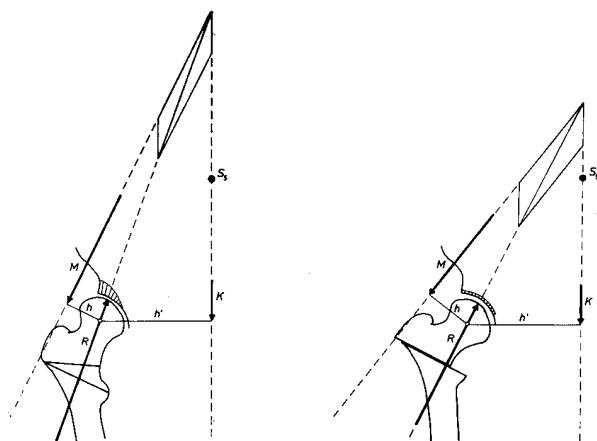


Fig. 7. — Mechanical effect of a varus intertrochanteric osteotomy. Same signs as in Fig. 1.

whereas the other remains normal. We deal here with *subluxating muscular imbalance*.

Provided that the articular surfaces are congruent, a proper varus intertrochanteric osteotomy (Pauwels I) lengthens the lever arm h of the muscles M (fig. 7). This enables the abductor muscles to balance force M with less force. The varus osteotomy also changes the direction of force M which becomes more inclined on the vertical. As a consequence, the angle formed by the lines of action of the forces K and M is opened. Opening of this angle and diminution of force M combine to decrease the resultant force R . Besides, the line of action of force R is moved medially to the depth of the acetabulum, which increases the weight bearing surface of this joint. Diminution of the force R transmitted across the joint and enlargement of the articular force transmitting surface both reduce the compressive stresses in the joint.

A 51-year-old female patient (fig. 8a) had developed painful osteoarthritis in a dysplastic hip. A dense triangle at the edge of the socket illustrated the reduction of the articular weight bearing surface and the localized increase of the compressive stresses in the joint. A 20° varus osteotomy was carried out. The dense triangle disappeared and was replaced by a thin ribbon of subchondral dense bone of even width throughout (fig. 8b). The pre-operative dense triangle occupied an arc of 75° . The arc covered by the postoperative

subchondral sclerosis has expanded to 107° . This is an objective demonstration of the increase in the weight bearing surface of the joint as well as of the decrease of the articular pressure. The follow-up is 19 years.

Carried out in a child, a varus osteotomy can have a remodelling effect. The resultant force R transmitted across the hip can be resolved into a longitudinal component L which pushes the femoral head upwards and a transverse component Q which pushes the femoral head inwards (fig. 9). The change of direction and the reduction of the resultant R due to a varus osteotomy significantly reduce the longitudinal push L . In spite of the diminution of force R , the transverse push Q is increased. This may result in a deepening of the socket during growth.

A 5-year-old child presented with a dysplastic hip and a shallow acetabulum (fig. 10a). A considerable varus osteotomy recentred the femoral head. Subsequently, the socket deepened significantly (fig. 10b). The follow-up is 18 years.

A varus osteotomy modifies not only the articular pressure but also the stressing of the femoral neck.

A 13-year-old female patient (fig. 11a) presented with osteoarthritis developing in a dysplastic hip. A dense triangle at the edge of the socket demonstrated the pathological increase of the articular pressure there. Longitudinal trabeculae occupied all the femoral neck and indicated that the neck was stressed in pure compression: the resultant R was acting in the core of the femoral neck. After a varus intertrochanteric osteotomy, the dense triangle in the roof of the socket was replaced by a subchondral sclerosis of even width throughout which demonstrates the diminution and better distribution of joint pressure over an increased force transmitting surface (fig. 11b). In the femoral neck two bundles of cancellous trabeculae indicate that the neck is now stressed in bending. The medial bundle corresponds to the trajectories of compressive stresses, the lateral bundle to the trajectories of tensile stresses. They surround Ward's triangle. These bundles form ogives typical of bending stressing with shear through a compressive force acting obliquely in relation to the axis of the femoral neck.

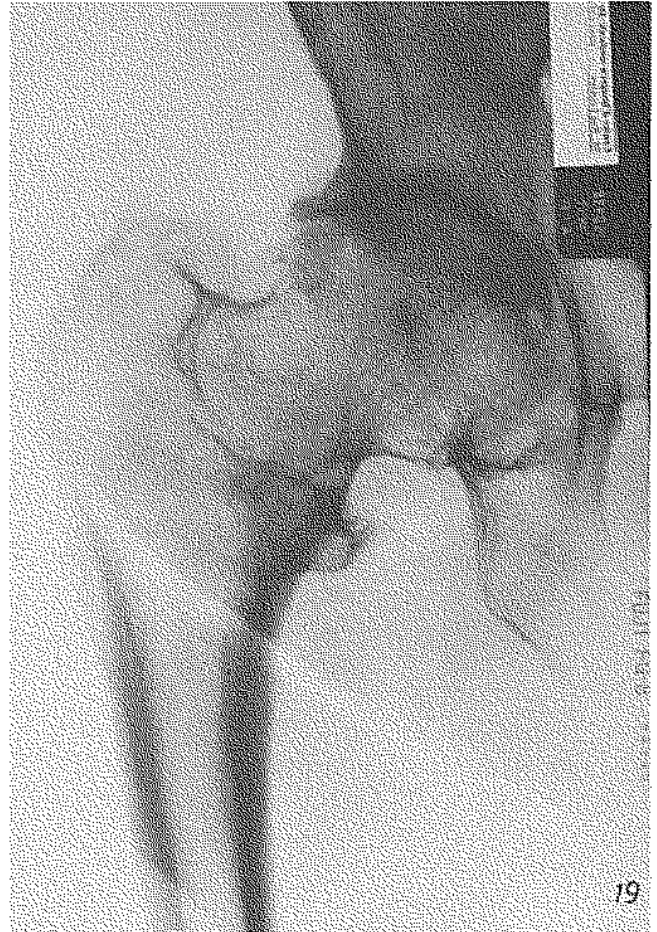
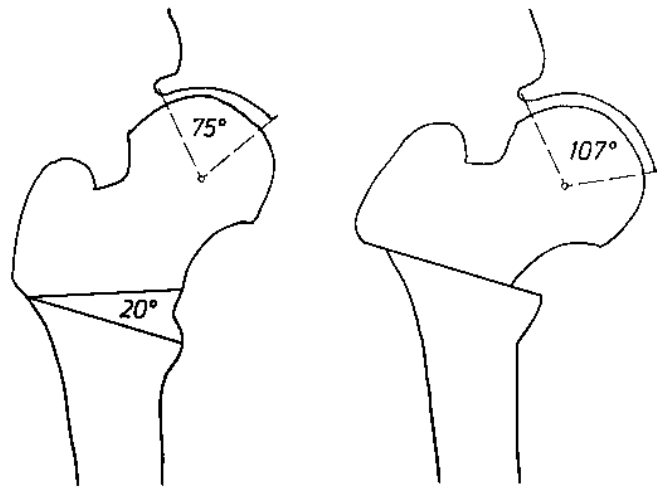
**a****b**

Fig. 8. — 51-year-old patient before (a) and 19 years after a varus intertrochanteric osteotomy (b). The force transmitting surface has expanded.

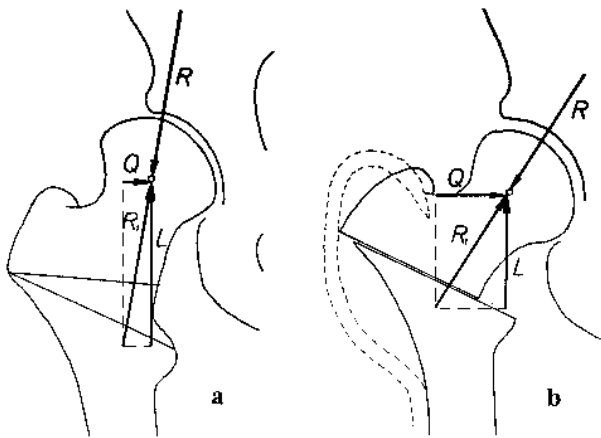


Fig. 9. — Mechanical effect of a varus osteotomy. Resolving the resultant force R into a longitudinal component L and a transverse component Q . *a* before a varus osteotomy; *b* after the varus osteotomy.

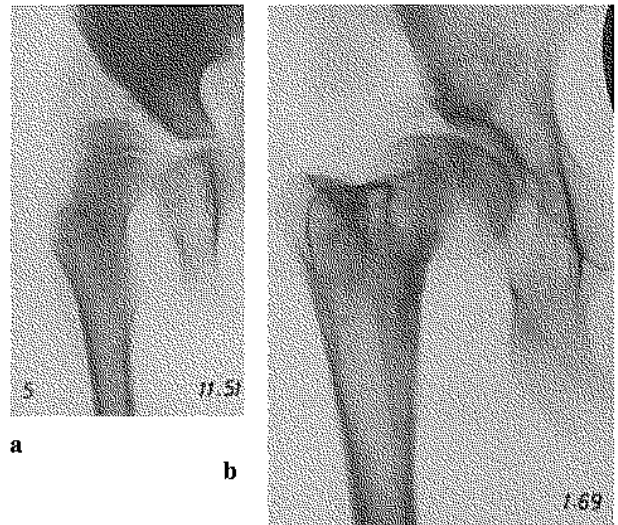


Fig. 10. — *a* 5-year-old child presenting with a subluxating hip dysplasia; *b* 18 years after a varus intertrochanteric osteotomy.

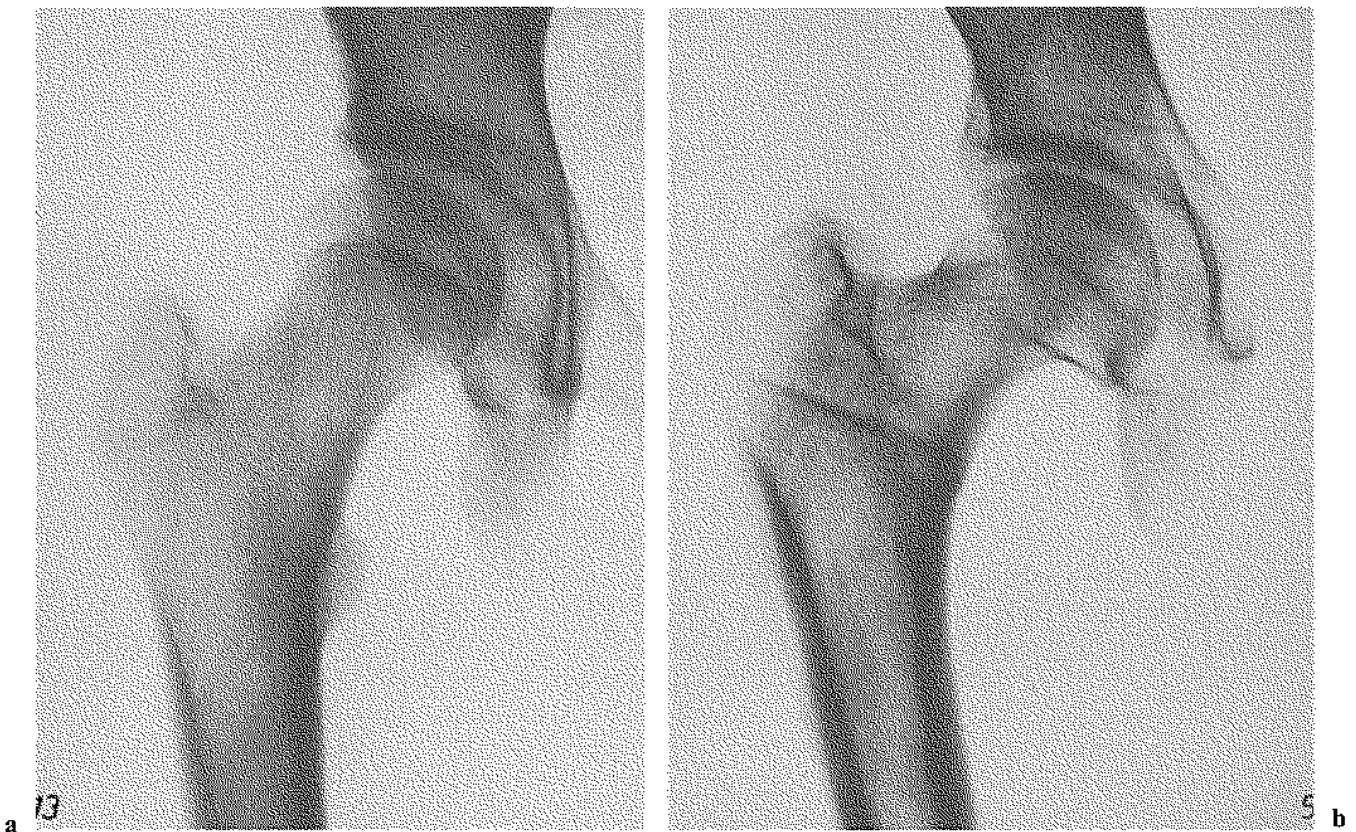


Fig. 11. — *a* Thirteen-year-old female patient presenting with a dense triangle at the edge of the socket. Longitudinal trabeculae occupy the whole femoral neck. *b* Five years after a varus intertrochanteric osteotomy, the dense triangle has been replaced by a thin ribbon of dense bone of even width throughout in the roof of the socket. Medial compressive trabeculae and lateral tensile trabeculae form ogives in the femoral neck stressed in bending and shear.

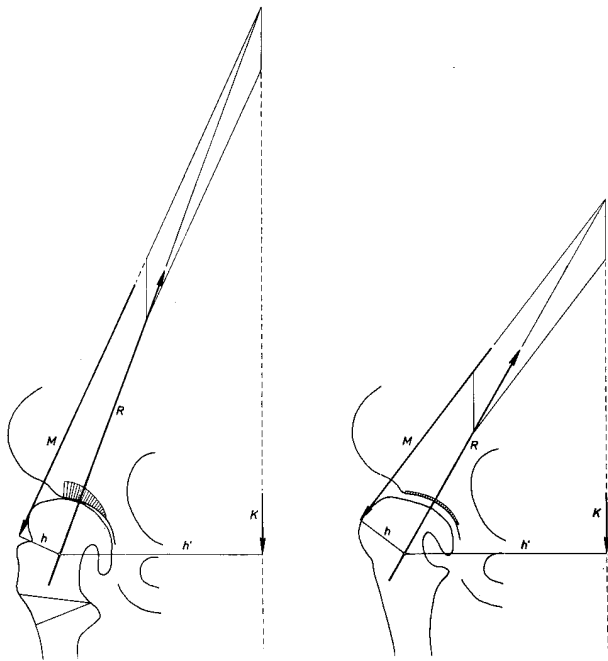


Fig. 12. — Mechanical effect of a valgus intertrochanteric osteotomy. Same signs as in Fig. 1.

During the evolution of osteoarthritis, the articular elements of the coxa valga subluxans undergo deformation to such a point that a varus osteotomy would no longer be able to ensure congruence of the articular surfaces. Then it is often possible to take advantage of the osteophyte developed over the medial aspect of the femoral head by making this osteophyte part of the weight bearing surface of the joint through a valgus intertrochanteric osteotomy.

A valgus intertrochanteric osteotomy (Pauwels II) turns the femoral head and makes it bulge outside the socket, pushing the abductor muscles away from the centre of rotation of the head and changing their direction (fig. 12). This results in lengthening of the lever arm h of the muscular force M and opening of the angle formed by the lines of action of the forces K and M . Both effects combine to reduce the resultant force R and to displace its line of action to the depth of the acetabulum. Reduction of force R and enlargement of the articular weight bearing surface both considerably diminish the compressive stresses in the joint.

A 37-year-old female patient presented with severe osteoarthritis developed in a subluxating dysplasia (fig. 13a). A varus intertrochanteric osteotomy would have brought anatomy closer to normal but, unable to ensure congruence of the articular surfaces, would have further decreased the weight bearing surface of the joint and increased the compressive stresses in the hip joint. A 25° valgus osteotomy was carried out, achieving congruence of the articular surfaces and thus decreasing pressure in the joint significantly. The clinical and xray result was excellent (fig. 13b). The follow-up is 30 years.

PROTRUSIVE DYSPLASIA

Coxa vara lengthens the lever arm h of the abductor muscles M (fig. 3b). These muscles thus can balance the force K due to the body mass with less effort. Moreover, the line of action of force M is more inclined on the vertical than in a normal hip, which opens the angle formed by the lines of action of forces K and M . Opening of this angle and reduction of force M combine to reduce force R . Additionally, the line of action of the resultant R is displaced medially in the acetabulum. This enlarges the weight bearing surface of the joint. Enlargement of the articular weight bearing surface and diminution of force R both reduce the compressive stresses in the joint. However, if force R is not exerted at the centre of the weight bearing surface but acts closer to the medial margin of the articular cartilage, pressure increases in the depth of the acetabulum: a dense triangle with medial basis develops (fig. 14). This is protrusive dysplasia.

Force R diverges from the axis of the femoral neck more than in a normal hip (fig. 3b). The stressing of the femoral neck in bending and shear, therefore, is more pronounced. This results in an accentuation of the compressive trabeculae medially and of the tensile trabeculae laterally with a well defined Ward's triangle in-between (fig. 4c).

In a hip the skeleton of which is normal, predominance of the transverse component of the abductor muscles M accentuates the inclination of the force M on the vertical (fig. 5c). This opens

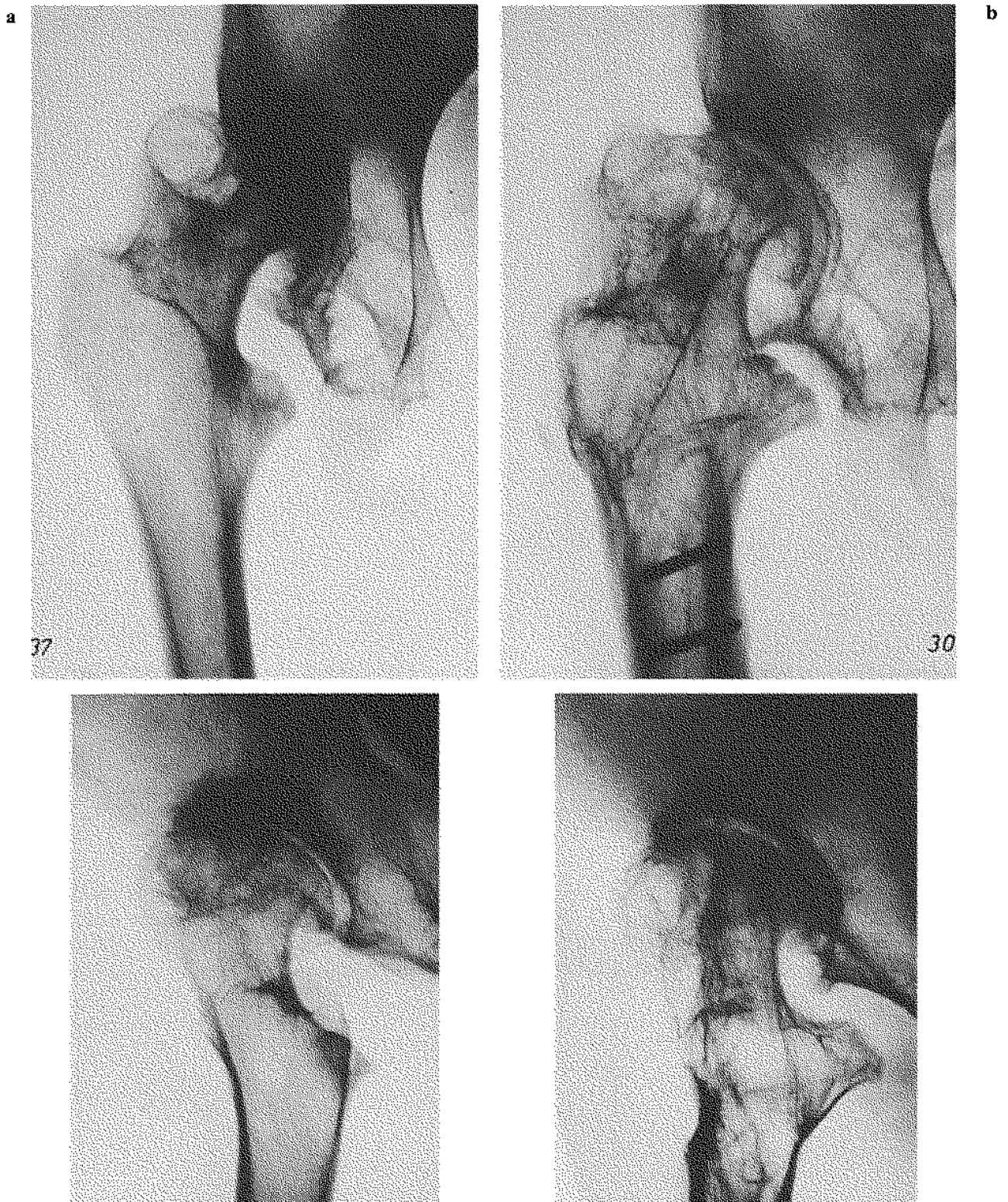


Fig. 13. — *a* Osteoarthritis in subluxating hip dysplasia in a 37-year-old female patient ; *b* Thirty years after a valgus intertrochanteric osteotomy.



Fig. 14. — Dense triangle in the depth of the socket in protrusio acetabuli.

the angle formed by forces K and M , and shifts the resultant R towards the depth of the socket. Acting closer to the medial margin of the articular cartilage, force R provokes there an increase of the articular compressive stresses. A triangle with a medial basis develops. We deal here with a *protrusive muscular imbalance*.

As described above, the resultant R can be resolved in a longitudinal component L and a transverse component Q (fig. 15). A valgus osteotomy, combined with a tenotomy of the adductor, abductor and ilio-psoas muscles, reduces the resultant R and moves its line of action closer to the vertical. This considerably reduces the transverse push Q and unloads the depth of the acetabulum.

A 58-year-old female patient presenting with a painful protrusive osteoarthritis (fig. 16a) underwent a valgus osteotomy. The sclerosis in the roof of the acetabulum became normalized and a wide joint space developed (fig. 16b). The follow-up is 10 years.

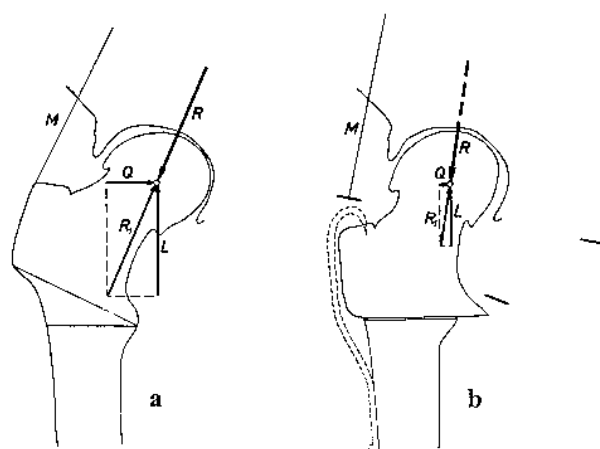


Fig. 15. — Resolving the resultant R into a longitudinal component L and a transverse component Q . *a* Protrusio; *b* Effect of a valgus intertrochanteric osteotomy.

In another work (Maquet, 1990), the dysplastic hip was analysed in its projection on a horizontal plane. It must be reminded that exaggerated ante-torsion of the femoral neck has the same effect on the hip as a coxa valga because the line of action of the force K due to the partial mass of the body, the line of action of the muscular force M and the centre of rotation of the femoral head must necessarily be in the same plane. This plane is determined by the line of action of force K and the centre of rotation of the femoral head.

CONCLUSION

Dysplasia of the hip, whether subluxating or protrusive, as well as muscular imbalance, very often entails considerable increase of the articular pressure in the hip joint and osteoarthritis of this joint. Sufficient diminution of the compressive stresses in the joint enables us to remedy to that to a large extent.

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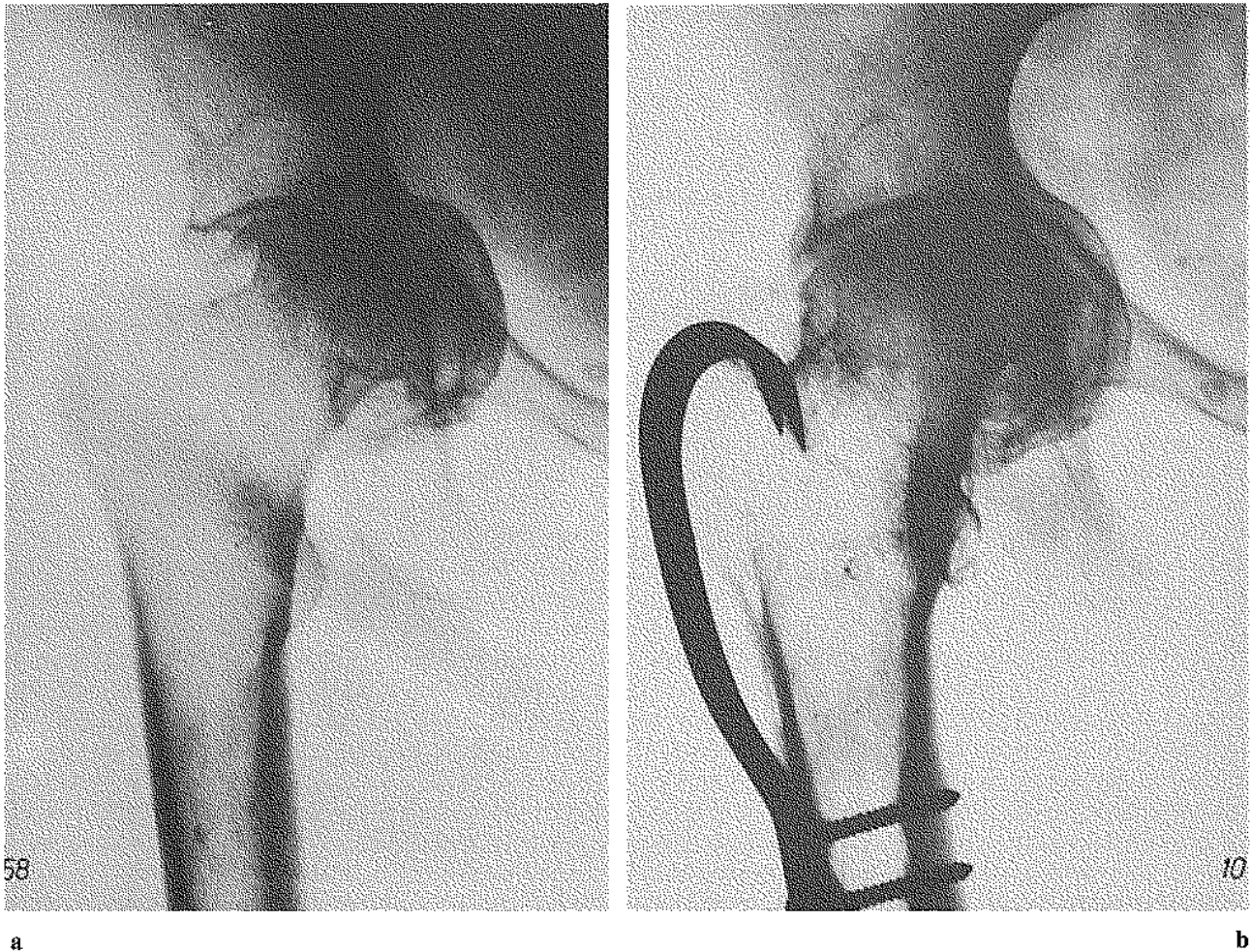


Fig. 16. — *a* Protrusive osteoarthrosis in a 58-year-old female patient ; *b* Ten years after a valgus intertrochanteric osteotomy.

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SAMENVATTING

P. MAQUET. Biomechanica van de dysplastische heup.

Tijdens de gang ondergaat de heup alternerend de lichaamsmassa minus het gewicht van het been. Deze massa oefent een kracht K uit op de heup met een krachttarm h' , deze wordt gecompenseerd door een spierkracht M van de abductoren met een krachttarm

h . De heup ondergaat dus de resultante R van de krachten K en M . Dit geeft stress en compressie in het gewricht. In de normale heup wordt de kracht R in het centrum van het contactoppervlak uitgeoefend en wordt de stress egaal verdeeld over het ganse oppervlak. Dit uit zich door een dunne laag sclerose subchondraal in het dak van het acetabulum. De normale femurhals ondergaat stress bij buiging en shear. Er is een mediale bundel van spongieuze trabeculae, gestressed in compressie en een laterale bundel, gestressed in extensie. Dysplasie en musculair onevenwicht hebben een gelijkaardig effect : een verkorting van arm h en een verticalisatie van kracht M . Verkorting van h vereist een toename van kracht M om K te compenseren ; de richtingsverandering van M , verplaatst de resultante R naar het uiteinde van het acetabulum. Dit heeft als gevolg een toename van R

gespreid over een kleiner oppervlak. Subluxatie van de heup door een te smal acetabulum geeft eveneens een grotere kracht R over een kleiner oppervlak. Deze ongelijke verdeling uit zich in een driehoekige sclerose op het uiteinde van het acetabulum ; dit is de aanvang van een subluxerende arthrose van de heup. Coxa vara heeft tegengestelde gevolgen : verlenging van arm h en een horizontalisatie van kracht M. Dit verkleint R welke mediaal verplaatst wordt en gespreid over een groter oppervlak met kleinere compressieve krachten in de heup. Wanneer het gewrichtskraakbeen zich niet verder ontwikkelt mediaal, verschijnen er oneven verdeelde krachten met een sclerosedriehoek mediaal. Dit is het begin van een protruserende arthrose. In coxa vara wordt de femurhals meer gestressed in buiging dan de normale heup, welke zich uit door meer spongieuze trabeculae welke loodrecht snijden in de femurkop.

RÉSUMÉ

P. MAQUET. Biomécanique de la hanche dysplasique.

Au cours de la marche, chaque hanche supporte alternativement la masse corporelle moins le membre inférieur sous-jacent. Cette masse exerce une force K qui agit sur la hanche avec un bras de levier h' ; elle est équilibrée par une force M exercée par les muscles abducteurs, agissant sur la hanche par l'intermédiaire d'un bras de levier h. La hanche transmet la résultante R des forces K et M ; la force R engendre des contraintes de compression dans l'articulation. Dans une hanche normale, la force R s'exerce au centre de la surface d'appui et les contraintes sont distribuées de façon régulière sur cette surface. Ceci se traduit par une mince sclérose sous-chondrale dans le toit du cotyle. Le col fémoral normal est sollicité en flexion

et cisaillement. Il présente un faisceau médial de trabécules spongieux, sollicité en compression, et qui s'entrecroise avec un faisceau latéral, sollicité en tension. Une dysplasie et un déséquilibre musculaire peuvent avoir les mêmes conséquences mécaniques : un raccourcissement du bras de levier h et une orientation plus verticale de la force M. Le raccourcissement de h a pour résultat une augmentation de la force M nécessaire pour équilibrer le moment de la force K, le changement de direction de la force M déplace la résultante R vers le bord du cotyle. Il en résulte une augmentation de la force résultante R qui se répartit de façon asymétrique sur une surface réduite. Une subluxation de la tête fémorale due à un cotyle dysplasique entraînera aussi une répartition inégale de la force R sur une surface réduite. La répartition anormale des contraintes de compression se traduit par le développement d'une sclérose triangulaire au bord du cotyle. C'est le début de l'arthrose subluxante de la hanche. La coxa vara a des conséquences inverses : allongement du bras de levier h des muscles abducteurs, et orientation plus horizontale de la force M. Il en résulte une réduction de la force résultante R, qui est déplacée médialement et s'exerce sur une surface plus étendue d'où des contraintes de compression moins élevées dans l'articulation. Si toutefois le cartilage articulaire du cotyle ne se développe pas du côté médial, la distribution des forces de compression peut devenir irrégulière, atteignant un maximum dans la région médiale, où se développe un triangle dense. C'est le début de la coxarthrose protrusive. Dans la coxa vara, le col fémoral est sollicité en flexion davantage que dans la hanche normale, ce qui se traduit par des trabécules spongieux plus marqués, qui s'entrecroisent à angle droit dans la tête fémorale. Le faisceau médial est sollicité en compression, le faisceau latéral en traction.