Balance of forces at the hip shown by models made from wood and wire – frontal plane

1. Basis of consideration: cable truss

The lightweight design is based on the triangle because of its structural stability. The elements of the triangle are stressed axially. The compression elements are subjected to buckling. Therefore they must be executed stiff (rigid). They are called rafters ore rods. The tension force can be transmitted by slack elements (ropes, cables). Then, we speak of a cable truss (Figure 1).

2. The two-leg stance (internal bracing)

2.1 Rhombus as base model

In the two-leg stance, the rigid elements are formed by the bones of the legs (tibia and femur) and the pelvis (neck of femur, iliac bone, sacrum). The center of gravity is located in the center of the sacrum (base of sacrum).

On the floor, the legs meet at one point. Therefore, a rhombus is formed. This rhombus is balancing.

As already mentioned, the both femur necks are components of the pelvis. The base of such a neck forms a pivot point (node).

The body weight acts as force F on the base of sacrum. In its further course, the force is transmitted through the pelvis and the legs to the feet and then on the ground and vice versa.

By inserting a „rope“, which connects the basis of the both femur necks, two triangles are created.
The supporting structure is treated as weightless.
The feet were brought together in one point, because of the oblique arrangement of the legs. As a result, horizontal forces are created which must be compensated.

A schematic representation of forces is given in Figure 2a. When a straight line is drawn from the base of femur neck to the feet, then the length of the legs are correctly reproduced. One can also prolong the femoral bones until they meet the line of outer load (dashed line), then the angle ratio (CCD angle) is properly shown. In the latter case, the pelvis-rope, herein referred to as pelvic floor, is stressed a little higher.

The amount of the respective forces is registered, they were calculated graphically.

The corresponding wood-wire model is shown in Figure 2b.

The lines of forces were sketched into a skeleton model (Figure 2c).

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Figure 2: Two-leg stance represented as the coupling of two triangles; a cable connects the basis of both necks
a) schematic force diagram, force values registered; the both femoral bones are dotted, load F as body weight (G)
b) wood-wire model under load (coarse scaled)
c) lines of forces drawn into an upright skeleton, S = center of gravity
2.2 Hip joint introduced

The nod of the hip joint is placed into the joint gap. The hip joint is supported by the ischium. Of major importance are the rotators, especially the quadratus femoris muscle. Attached at basis of the femur neck, they pull to the ischium, where they produce a bending moment. To compensate the bending moment, the ischium is held by the sacrotuberous ligament, which leads to the center of the sacrum.

In the horizontal plane, the pelvis is held together by the sacrospinous ligament. Divided into two branches, it leads horizontally from the hip joint to the lower part of the sacrum and then further to the opposite hip joint.

The rotators provide a load-dependent modulation of the stresses in the femur neck. As a result, bending is avoided there.

The calculated forces scheme is given in Figure 3a. The wood-wire model is shown in Figure 3b. The lines of forces are drawn into an X-ray image (Figure 3c).

![Diagram of forces in the hip joint](image)

Figure 3:
Hip joint introduced;
ischium as a support

a) schematic diagram of the forces.

Both femurs were prolonged to the line of outer load.

The rotators respectively connect the basis of the femur neck with the ischium.
Figure 3 continued:
b) Wood-wire model:
muscles represented by red wire, ligaments by blue wire

c) The lines of forces are drawn into an X-ray image
(female, about 50 years old)
2.3 Sacroiliac joint introduced

The sacrum is a broad bone. Its horizontal branches are referred to as „pars lateralis“ or „ala of sacrum“. The surfaces of the sacroiliac joint are relatively large.

As in the case of the hip joint, the nod of the sacroiliac joint is placed into the joint space.

From the hip joint the force rises steeply and follows strictly the body of ilium until it reaches the sacroiliac joint. Then the force runs horizontally through the ala of sacrum to the center of the sacrum (base of sacrum).

From the sacroiliac joint, the sacrum is held in place by ligaments which pull to the lower part of the sacrum. The sacroiliac ligaments are strongly fanned. They hold the sacrum is in a loop.

The force diagram is given in Figure 4a. The wood-wire model is shown in Figure 4b.

The lines of forces are again shown in a radiograph (Figure 4c).

![Figure 4: Introduction of sacroiliac joint](image.png)
a) schematic force diagram;
ligaments form a loop, in which the sacrum is suspended.
Figure 4 continued
b) Wood-wire model: red wire as muscles, blue wire as ligaments

c) representation of the forces on the radiograph
3. Passive one-leg stance (without inclusion of back muscles)

3.1 Tower crane

Two basic types of tower cranes are used
- only the jibs rotate (slewing unit at the top of the tower)
- the whole tower rotates (slewing unit at the bottom of the tower)

For our considerations, the second type is of interest:

The tower („mast”) is attached to the slewing platform which also carries a rack and the counterweight.

The load jib of this kind of crane can be inclined in the vertical direction („luffing jib”). Three triangles stabilize the crane. In Figure 5a these triangles are sketched into a photo of a real crane by different colors (green, red, blue).

Green triangle: this triangle is formed by load jib, the counter jib and the jib guy line (luffing rope).

Red triangle: It is formed by the tower, the counter jib and the luffing rope. The rope is prolonged by the inner struts of the rack.

Blue triangle: Tower (half height), slewing platform and outer struts of the rack, the latter prolonged by the tower guy lines.

The both first triangles stabilize the load jib. By means of the third triangle the crane is erected and maintained upright. The load is carried by the hoist rope.

Would you bring the foot of the tower crane just under the load, the crane became able to balance (without a need for a counterweight) and it would only require two triangles.

A schematic representation of one-leg stance is represented in Figure 5b. The extended iliotibial tract serves as the jib guy line. The counter jib is represented by the trochanter major; it is regarded as a sheave.

In the present wood-wire-model, a rope pulley acts as trochanter. This pulley was taken from a metal construction kit (Figure 5c).

When our skeleton model is inclined a little above the main pillar, such a balancing crane can be introduced (Figure 5d). The model used here is stiff in the spine.
Figure 5: Tower crane as basic principle of the one-leg stance
a) bottom slewing tower crane with luffing jib, counterweight below (crane type: Mostostal M-120/160)
b) forces scheme, load jib as pelvis, greater trochanter as counter-jib, iliotibial tract = jib guy line
c) wood-wire model, a rope pulley serves as trochanter and leads the jib guy line
d) crane sketched into the skeleton which is inclined so that the center of gravity is arranged above the main pillar (stiff spine)
3.2 Hip joint introduced

Into the load jib the hip joint is inserted. As in the case of the two-leg stance, the hip joint is supported from below by the ischium. From above the wing of iliac bone (ala ossis ilii) presses against the hip joint. Thus, the bones form a cross. At their outer ends the parts of the cross are held together by muscles and ligaments. Again, a load-dependent modulation is provided by the rotators pulling from the base of the femur neck to the ischium. In Figure 6, the force diagram is shown in (a), the wood-wire model in (b) and the X-ray image with sketched lines of forces in (c).

Figure 6: Hip joint introduced into the load jib; the joint is supported by the ischium and the wing of ilium
a) schematic forces (femur prolonged to the line of external forces)
   b) wood-wire model: muscles represented by the red wire, ligaments by blue wire
Figure 6 continued:
c) lines of forces drawn into a radiograph
3.3 Introduction of the sacroiliac joint and the knee joint

The sacroiliac joint is put into the pelvis and the knee joint into the leg. The completion of the pelvis framework follows the example of Figure 4.

At the knee there are two nodes, namely the center of the knee (patella) and its lateral edge. At the latter point the actual iliotibial tract inserts. By a branch of this band, which aims at the patella (here referred to as the suprapatellar tract), we get the physiological knock-knee (Figure 7a-c).

Figure 7: Sacroiliac joint and knee introduced
a) force scheme; physiological knock-knee due to the „suprapatellar tract“ acting on the middle of the knee
b) wood-wire model: muscles made of red wire, ligaments of blue wire.
4. Active stance on one leg by including the lateral back muscles

When man is walking, he uses the upper body as a flywheel. Therefore it should be considered in which kind the upper body interacts with the pelvis. In our model, the center of gravity is raised in the upper part of the lumbar spine. The whole system is erected a little.

4.1 Basic principle (advanced tower crane)

In the schematic representation, the corresponding basic crane is described as shown in Figure 5:

The pelvis, consisting of the femur neck and iliac bone, forms the central load jib. As a further load jib, the lumbar spine is placed on the central jib.

The lumbar spine is inclined to the medial side (above the main pillar). The lateral back muscle (quadratus lumborum muscle) of side of the free leg prevents the spine from tilting down. It results in a force that runs to the lateral side the sacrum. There, it inserts at the sacroiliac joint. The extended lateral rotators stretch back from sacroiliac joint to the basis of the femur neck, see Figure 8a.

The corresponding wood-wire-model shows that this kind of loading is in principle possible (Figure 8b). In Figure 8c, the force profile was transferred to our skeleton man.
Figure 8: Man walking; basic system analogous to Figure 5

a) schematic forces; the lumbar spine is set onto the pelvis jib. Against tilting to the medial side, the lumbar spine is hold in place by the lateral back muscle, which in turn is opposed by the extended rotators. The iliotibial tract of the main pillar stabilizes the whole.

b) wood-wire model; bands made of white wire, muscles of red wire

c) skeleton model; the center of gravity is arranged into the upper part of lumbar spine; crane plotted, the spine was curved a little by plotting method
4.2 Pelvis completed

In Figure 9, the pelvic framework is completed by including the hip and the sacroiliac joint (compare Figures 4 and 5).

The upper body is stabilized by a string consisting of the quadratus lumborum muscle, short pelvic ligaments (sacroiliac ligaments) and the gluteus maximus. From the lower sacral region the latter runs in the direction of the iliotibial tract at which it inserts from the side. The force required by this side pull is rather small. Thus, the gluteus maximus muscle gets able for acting on the lumbar spine from behind, which provides the basis for the upright walking.

When the owner of the pelvis was exposed to the X-ray investigation, he did not knowingly stand on one leg. The inclination of its spine could also reflect his scoliosis.

Figure 9: Walking of man, upper body inclined above the main pillar; medial displacement of the load line to the longitudinal axis of the pelvis (to line c); stressing of the iliotibial tract by the gluteus maximus from the side of the lower sacral region
a) schematic forces, side pull of the gluteus maximus on the iliotibial tract
b) wood-wire model, blue wire for ligaments, red wire for muscles
5. Ventral tensioning system

The collum neck is not perpendicularly directed to the pelvis, but at about 15° to the front, which is termed as anteversion. Thus, the hip joint has to be supported with respect to the side view (sagittal plane). The required force is delivered by the pubic bone. This bone needs also a stabilization. Concerning the upper direction, the outer end of the pubic bone is stressed by the inguinal ligament. This force is counteracted by the pubofermoral ligament (Figure 10). Compared to the true anatomical relations, here the upper end of the inguinal ligament is attached at the ilium slightly increased (iliac crest instead of anterior superior iliac spine). The aim was to get a defined node.
Figure 10: Ventral tensioning system
a) scheme of forces, hip joint supported by the pubic bone; inguinal ligament as well as pubofemoral ligament stabilize the pubic bone
b) Wood-wire model: no muscles, only bands (blue)
c) X-ray image with marked force lines
In the explanation of the two-leg stance, the physiological knock-knee was neglected. To incorporate this, you should take two pieces of one-leg crane facing each other and connect them to the upper point of load application. Then the forces are halved. Thus, the true two-leg stance is based also on an external bracing.

Summary

For static computation, the base of the femur neck is considered in the same way as an anatomical joint. This assumption is justified by the presence of the rotator muscles, which produce a horizontal force for a load-dependent modulation.

As a result, a structure (scaffold) is produced in which the bones are loaded axially in compression. Concerning the surfaces of the involved joints (knee, hip, iliosacral joint and base of sacrum), it follows that the stresses are evenly distributed.

By means of wood-wire models, which were photographed under load, these relations are shown impressively.

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See the details in:

In the original published 1992, pp. 81-92, eBook ISBN: 978-3-11-087567-6:
This article can also be found in this website. There are further contributions concerning the two-leg stance and the top view of hip region.