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STRESS AND STRAIN ANALYSIS IN THE PELVIC BONE

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Abstract: In the musculoskeletal system, the pelvis is one of the most important components. The entire body rests on this construction. The role of the pelvis is to transfer gravitational and external load across the sacro-illiac joints and the hip joints. The purpose of this study is to observe the stress and strain distribution in the pelvic bone. Due to its complex geometry and structure, the biomechanics of pelvis is complicated. The Finite Element Method (FEM) may be used to analyze this type of very complex geometries. To get the realistic results, the finite element analysis have to be accomplished with a three-dimensional model similar to the shape and architecture of the pelvic bone. Computer tomography scan data is used to create such a model. The static downward load of 800 N corresponding to the average weight of the human body as well as the appropriate forces exerted by the muscles under normal walking condition are applied to the model. Numerical computation results are presented in form of the stress and strain maps.

1. Introduction

The pelvic girdle supports and protects the contained viscera and affords surfaces for the attachments of the trunk and lower limb muscles. Its most important mechanical function, however, is to transmit the weight of the trunk and upper limbs to the lower extremities.

It may be divided into two arches by a vertical plane passing through the acetabular cavities; the posterior of these arches is the one chiefly concerned in the function of transmitting the weight. Its essential parts are the upper three sacral vertebræ and two strong pillars of bone running from the sacro-iliac articulations to the acetabular cavities. For the reception and diffusion of the weight each acetabular cavity is strengthened by two additional bars running toward the pubis and ischium. In order to lessen concussion in rapid changes of distribution of the weight, joints (sacro-iliac articulations) are interposed between the sacrum and the iliac bones; an accessory joint (pubic symphysis) exists in the middle of the anterior arch. The sacrum forms the summit of the posterior arch; the weight transmitted falls on it at the lumbosacral articulation and, theoretically, has a component in each of two directions. One component of the force is expended in driving the sacrum downward and backward between the iliac bones, while the other thrusts the upper end of the sacrum downward and forward toward the pelvic cavity [3,4].

A pelvic bone is a very important element of the hip joint. Its correct shape and load decide about human locomotive abilities. Contemporary achievements in medicine and technics allow to correct deformed or damaged bones. Knowledge of strain and stress state in a pelvic bone in both the anatomically correct state and degeneration (disease conditions) or damage allows for better diagnosis and preparation of operations.

2. Numerical model of the pelvis

In numerical investigations two main problems occur. The problems are connected with preparation of a computational model. The first problem is connected with faithful numerical imitation of real features of a natural human pelvic bone. The second one concerns modeling of the load.

Earlier investigations were based on geometric data manually prepared from clinical samples. Presently, geometry of a pelvis is assumed on the basis of scanning measurements, performed by means of computer-assisted tomography (CAT). During the scanning we get outer contours of sections, obtained by "cuts" of the pelvic bone with a number of parallel planes (Fig. 1).

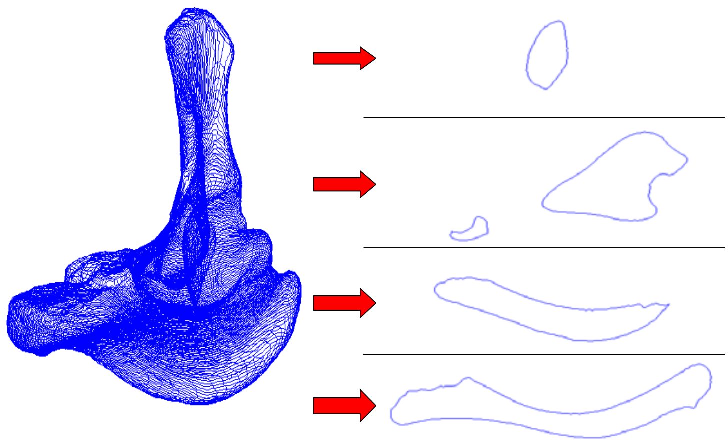


Fig. 1. External contours of the human pelvis sections for different scanning layers

Determination of the strain and stress distribution is a task of strength analysis strength analysis. For bodies of complex gemoetry, obtaining of reliable results is possible only by applying numerical methods, in particular the Finite Element Method.

In this paper, the numerical modeling has been performed by means of Ansys 7.1 Workbench. During the analysis we ignored a complex structure of osseous tissue and assumed homogeneous elastic properties. Young's modulus is taken at 20000 MPa, and the Poisson ratio at 0,3.

In the assumed numerical model we applied the following scheme of support (Fig. 2):

1. a contact surface of the pelvic bone and the sacral bone,
2. a contact edge of the pubic symphysis,
3. a contact surface of the acetabulum cooperating with the femur head.

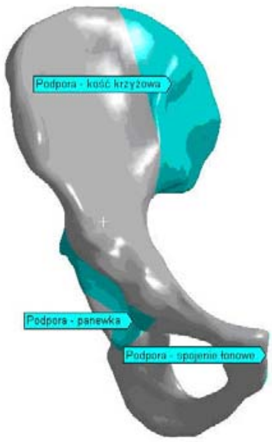


Fig. 2. Support scheme for numerical model

Fig. 3 illustrates a numerical model of the pelvic bone with segmentation into finite elements. The assumed numerical model consists of 3917 elements of triangular shape spanned on 7226 nodes. The segmentation into finite elements has been performed by means of Ansys 7.1 Workbench.

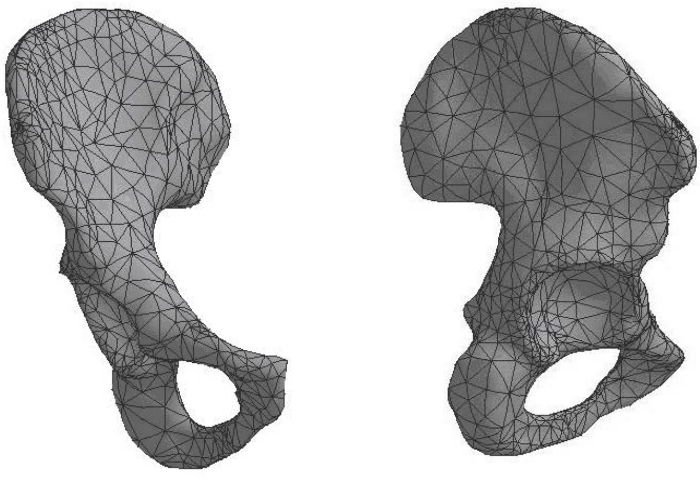


Fig. 3. Model of the pelvic bone with segmentation into finite elements (two projections)

3. Pelvic bone load modeling

Stress and strain state of a pelvic bone is a consequence of external load, which comes from the weight of the upper part of a body (Fig. 4) and muscle forces affecting this bone by means of tendons at attachment points (Fig. 5).

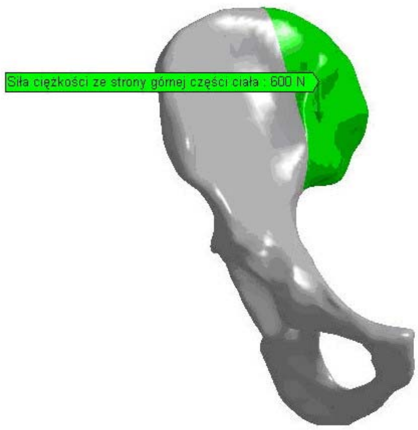


Fig. 4. Pelvic bone model with the applied force due to the weight of the upper part body

In the analyzed model we assumed 23 muscle actons influencing the pelvic bone as they realize their basic functions in the motion process, i.e. flexion, extension, adduction and abduction. Muscle actons are attached by one end to the pelvic bone and the second end to the femur or the shinbones. Location of the muscle relative to the bone and joints is connected with its function in the locomotive system [1, 2, 4].

Muscle forces influencing the pelvic bone by means of tendons are applied at muscle attachment points and presented in the model in a form of continuously distributed load, inclined to the surface of the pelvic bone at the angle determined by direction cosines of action lines of appropriate muscle actons [2].

Values of direction cosines in the global coordinate system and lengths l of particular muscle actons have been evaluated on the basis of coordinates of the muscle attachment points corresponding to centers of attachment surfaces, which have been determined by outcomes of the measurements performed on the model of the hip joint. The rest length $l_0 = 0.8 \cdot l$ has been evaluated for each acton. This length corresponds to maximal value of muscle force under isometric conditions F_{max}.

Values of the forces F_{max} for each acton have been evaluated as a product of its physiological section A and a maximal value of stresses in the actively excited muscle, which is assumed in the literature as $\sigma_{max} = 0.5$ MPa.

Basing on the values of maximal shortening of the actons, measured on a model of a correct hip joint in ranges of flexion and extension movements in saggital and frontal planes, one determined limiting values of unit shortening of each acton Δl/lo. We also evaluated values of unit elongation of the actons after pelvis osteothomy $(\Delta l_1+l_0)/l_0$, (Δl_1 - elongation of the acton after the treatment for the osteotome angle α=30°).

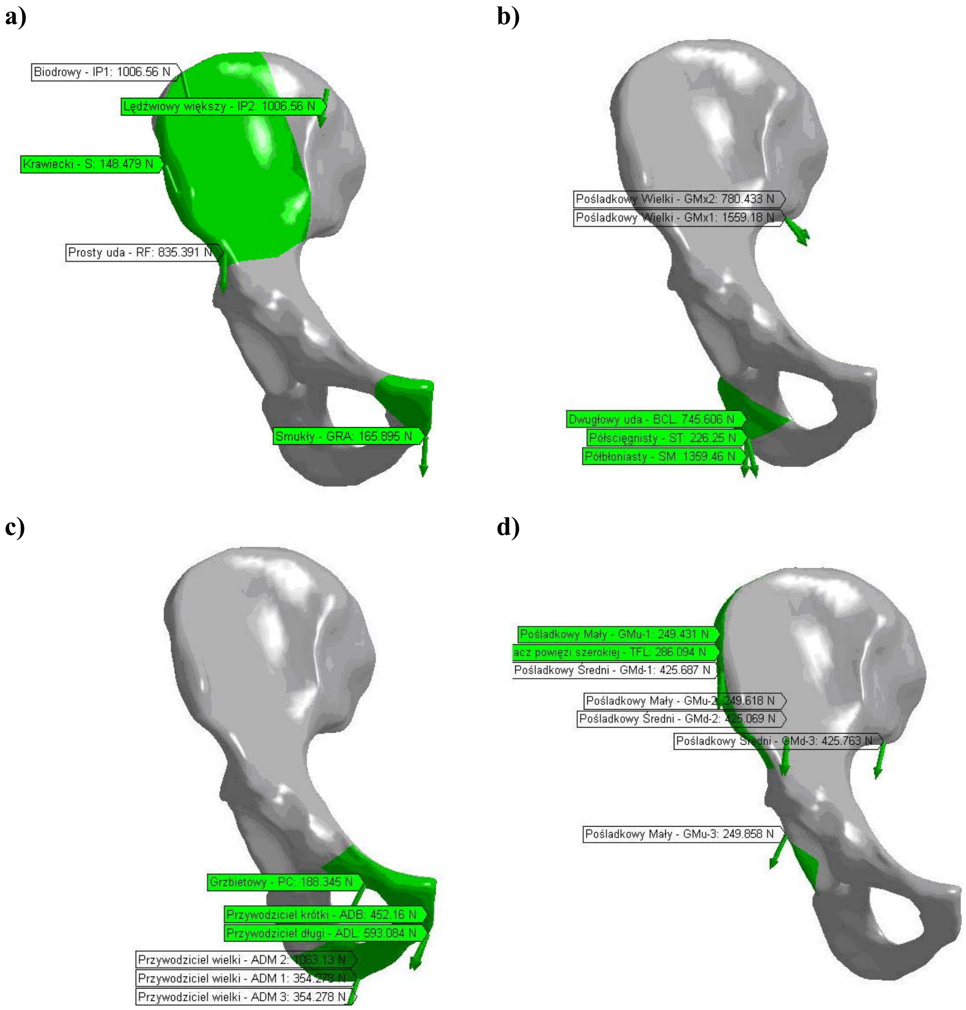


Fig. 5. Vectors of the muscle forces during: a) flexion, b) extension, c) abduction, d) adduction.

The values of muscle parameters, given in Tab. 1, give a possibility of constructing physiologically justified models of load of the pelvic bone. The parameters are also a basis to estimating possible change ranges of forces, which follows from the muscle characteristics.

Table 1. Selected muscle parameters characterizing the action of the muscles on the pelvis

	Muscle	**l [mm]**	**l_0 [mm]**	**$\Delta l/l_0$**	**$(\Delta l_1+l_0)/l_0$**	**A [cm^2]**	**F_{max} [N]**
Flexors							
1	RF	385	308	0,19	0,97	16,69	835
2	S	455	364	0,37	1,07	2,95	148
3	IP1	233	187	0,32	1,19	20,1	1006
4	IP2	388	310	0,20	1,25	20,1	1006
5	GRA	366	293	0,14	1,05	3,30	165
Extensors							
6	GMx-1	134	107	0,49	1,18	31,18	1559
7	GMx-2	159	128	0,41	1,15	15,60	780
8	ST	342	273	0,27	1,07	4,51	226
9	SM	347	277	0,27	1,08	27,18	1359
10	BCL	346	277	0,36	1,10	14,89	745
Adductors							
11	ADM-1	114	91	0,99	1,30	7,08	354
12	ADM-2	195	156	0,58	1,18	21,25	1063
13	ADM-3	302	242	0,37	1,10	7,08	354
14	ADL	189	151	0,59	1,06	11,85	593
15	ADB	130	104	0,86	1,18	9,04	452
16	PC	128	102	0,39	1,07	3,76	188
Abductors and muscles stabilizing pelvis							
17	GMd-1	136	109	0,38	1,23	8,50	425
18	GMd-2	146	117	0,36	1,24	8,50	425
19	GMd-3	145	116	0,36	1,23	8,50	425
20	Gmu-1	112	90	0,47	1,29	4,97	249
21	GMu-2	117	94	0,45	1,30	4,97	249
22	Gmu-3	119	95	0,44	1,25	4,97	249
23	TFL	457	365	0,42	1,08	5,71	286

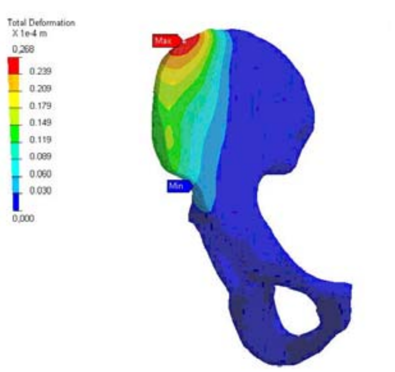
Symbols:

l - muscle acton length, l_0 - muscle acton resting length, $\Delta l/l_0$ - unit shortening limit value of muscle acton, $(\Delta l_1+l_o)/l_o$ - unit elongation of muscle acton, A - physiological section area of muscle acton, F_{max} - maximum value of the muscle force, RF - rectus femoris, S - sartorius, IP - iliopsoas: IP1 - iliacus, IP2 - psoas major, GRA - gracilis, GMx - gluteus maximus, ST – semitendinosus, SM – semimembranosus, BCL – biceps femoris caput longum, ADM – adductor magnus, ADL – adductor longus, ADB - adductor brevis, PC – pectineus, GMd – gluteus medius, Gmu – gluteus minimus, TFL – tensor fasciae-latae

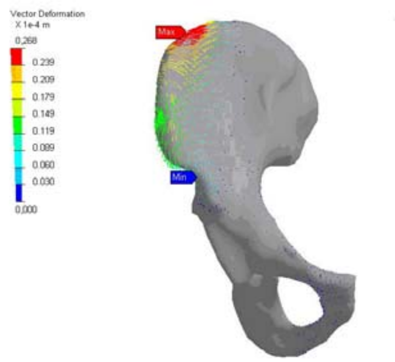
4. Numerical results

For the assumed model of the pelvic bone, loaded by weight of the body and by forces coming from the muscle actons, one has determined the total strain, vector strain, maximal principal stress, normal stress and the safety factor. Computations have been performed for particular functions of the locomotive system: flexion, extension, adduction and abduction.

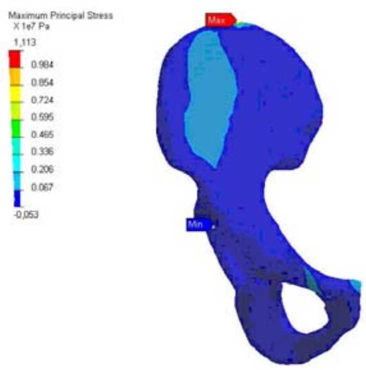
a)



b)



c)



d)

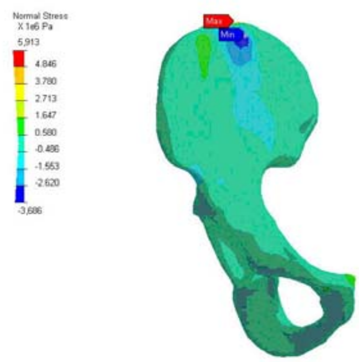


Fig. 6. Stress and strains in the pelvic bone during the flexion: a) total deformation, b) vector deformation, c) maximum principal stress, d) normal stress

In Fig. 6, one presented an exemplary distribution of strains and stresses in the human pelvic bone for flexion. A place of the largest strains is iliac spine in this case. The largest values of the maximum normal stresses occur in the vicinity of iliac crest and they equal 11,13 MPa.

Maximal principal stresses, during flexion, are located in a region of contact between the acetabulum and the femur head and they equal 9,88 MPa.

The largest strains during the abduction occur in the vicinity of ischium and equal 0,13 mm. It should be noted that these are the largest strains of all the presented functions of motion. In the neighborhood of the support, namely in the acetabulum, next to the sacral bone and the pubic symphysis, displacements are nearly zero.

Vectors of muscle actons interactions have a significant influence on the direction of strains. Direction of these strains approximately coincides with directions of vectors coming from the muscle forces.

Maximal direct stresses occur during the abduction in a region of ischium and reach 22,33 MPa, whereas the smallest value of these stresses equal 9,88 MPa. Thus, a ratio of maximal to minimal stresses is 225%. It should be noted that a region of occurrence of maximal stresses is not big.

Analyzing the maximal values of direct stress we can observe that the values are largest during the abduction, like maximal principal stresses. The maximal values of direct stress reach 15,78 MPa and occur on pubic symphysis .

The value of the safety factor in each of motion function did not go down below 15. This means that the pelvic bone subjected to typical loads occurring during the calm gait is not liable to any damages. High value of the safety factor shows that it is possible to load the pelvic bone by significant dynamical forces (running, jumps) without anxiety about its damage.

The goal of the above results was to present the influence of load, acting on the pelvic bone. It should be emphasized that the investigation did not refer to each function of motion alone, and forces coming from the muscles had a maximal value.

5. Concluding remarks

By the analysis of the stress and strain of the pelvic bone we can investigate phenomena running under physiological loads of bones stimulating biotic processes of tissues as well as incorrect loads, which are consequences of abnormality in bones structures, hip joint and the muscle system. This issue is an interesting problem and object of interests of orthopedists, especially with regard to results of surgical interventions.

The most important conclusions following the strength analysis can be formulated as follows:

- the largest strains occur during the adduction in the vicinity of ischium;

- the smallest strains of the pelvic bone occur at the following contact points: the pelvic bone and the sacral bone, the pubic symphysis and the acetabulum;
- maximum principal stresses occur during the abduction in a region of ischium;
- maximum value of normal stresses occur on the pubic symphysis during the adduction;
- change of value of Young's modulus and the Poisson ratio for the pelvic bone have not a significant influence on the change of value of stresses and strains;
- direction of vector strains in the model of a pelvis is strongly dependent on directions of vectors coming from muscle actons;
- a place of maximum principal stresses occurrence coincides with places of muscle attachments;
- during the human gait the maximum principal stresses and total strains occur in the initial phase of the contact between a foot and a ground.

The performed analysis does not cover all problems connected with stresses and strains of a pelvic bone. Widely understood dynamical aspects occurring e.g. in some sport disciplines (running, jumping) require further investigations. Moreover, one needs to make a thorough study of situations, in which the pelvic bone is liable about a very large impact-like load, e.g. car accidents. It also seems that continuous improving of imaging techniques of a human body CT scanning, nuclear magnetic resonance (NMR) should have find the reflection in the improvement of the model itself of the pelvic bone in geometry, load modeling and materials characteristics.

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