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Analysis of Muscle Forces Acting on Fragments in Pelvic Fractures

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A B S T R A C T

CT was used in 50 adult pelvic fractures to determine the size and the position of relevant muscles with regard to bony elements in order to calculate muscle forces acting upon certain pelvic portions. Muscle length was measured to calculate muscle volume and physiological muscle cross-section. Among others, the size and direction of muscle forces were calculated for iliac, pubic and ischiadic fractures. The strongest muscle acting in iliac fractures is m. gluteus medius. The strongest upward pulling of iliac bone fragments is exerted by the erector muscles, while the major anterior, medial and downward pulling is performed by the iliopsoas muscle. In pubic bone fractures, eight muscles push bone fragments downward, the strongest among them being m. adductor magnus. *Two muscles pull them upwards: m.rectus abdominis and* m. obliquus externus. *Nine muscles are responsible for downward displacement of bone fragments in ischiadic fractures, but the strongest is* m. semitendinosus. *Calculation of moments of muscle forces acting upon bone fragments using CT of pelvic fractures gives additional data for planning of optimal operative treatment that can guarantee stable fixation in individual patients.*

Key words: *pelvic ring, CT muscular morphometry, pelvic fractures, biomechanics*

Introduction

Pelvic fractures are produced by direct or indirect forces acting upon fracture fragments[1] or the entire pelvis (Watson-Jones 1955; Nigst 1981; Jude 1964). After a fracture has occurred, muscle and other internal forces[2] determine the spatial position of bone fragments and their stability. Knowledge about the spatial position of fracture fragments, fracture gap position, volume and position of muscles acting upon bone fragments in pelvic fractures serves as the basis for approximate calculation of the magnitude and direction of muscle forces[3] acting upon fracture fragments. The aim of this study is to define the magnitude and direction of the resulting forces that act upon fracture fragments using computed tomography[4].

Understanding basic properties of allenthesis[5] is important for planning of fracture fixation that is stable enough to withstand all static and dynamic forces during the entire process of fracture healing, without fixation failure or implant breaking due to fatigue of the implant material.

Material and Methods

CT scans were performed in 50 adult patients with pelvic fractures of various shapes and types. Indication for CT was the need to define precisely the spatial position of bone fragments in instable pelvis fractures in order to make operative planning. Scanning was performed at the angle of 90° to the longitudinal body axis, i.e. at the angle of 90° to the table.

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The following tasks were performed: 1. analysis of the cross-section and position of muscles in relation to bony elements as well as analysis of muscle volume; 2. calculation of forces acting on certain pelvic portions.

Using data on muscle length (L) that can be approximately measured on tomograms and by extrapolation and interpolation of the portions approximated to the scalene cone, we determined the approximate volume of muscles (V). This calculation was excluded if there were not sufficient data for such a calculation. Based on the data collected by Friedrich and Brand[6], who calculated the ratio between the length of the entire muscle and the length of muscle fibers[7], we calculated the length of muscle fibers using measured muscle lengths. CT does not show the physiological cross-section of muscles (FA) but it displays anatomical cross-section of muscle[8] (A). Therefore, we had to calculate the physiological cross-section using data on muscle volume in the following way: the muscle volume was divided with the length of muscle fibers. In addition to data on muscle strength[9], which is proportional to the physiological cross-section measured on tomograms, we can also obtain data on the direction of the force acting on bone fragments[10]. The distance between the centroid of the muscle cross-section and the fragment corresponds approximately to the arm of the acting force. In case of pinnate muscles, where muscle fibers access the muscle tendon at a specific angle that indicates the direction of muscle force or where muscles are positioned at a specific angle towards the bone, the physiological cross-section of the muscle[11] is not proportional with the acting muscle force. In this case, the physiological cross-section of the muscle must be multiplied by the cosinus of the average angle between muscle fibers and the bone.

Results

The upper top slice of CT passes through the lumbar region at the level of the fourth lumbar vertebra. This slice shows abdominal and lumbar muscles. At the same time, density of the cancellous bone in the middle of the fourth lumbar vertebra is measured in this slice, in order to check for possible osteoporosis[12].

The next slice is done at the level of the widest portion of the iliac crest. This image shows iliac wings and the upper portion of the sacral bone. The surface of cross--sections of the posterior muscle group is determined in this slice (larger part of *the m. gluteus maior* and only a small part of the *m. gluteus medius*)[13] and the surface of the cross-section of the *m.ilipsoas* is determined on the anterior side. At this level, abdominal muscles (partly lateral abdominal muscles and the lower segment of the straight abdominal muscles)[14] are displayed.

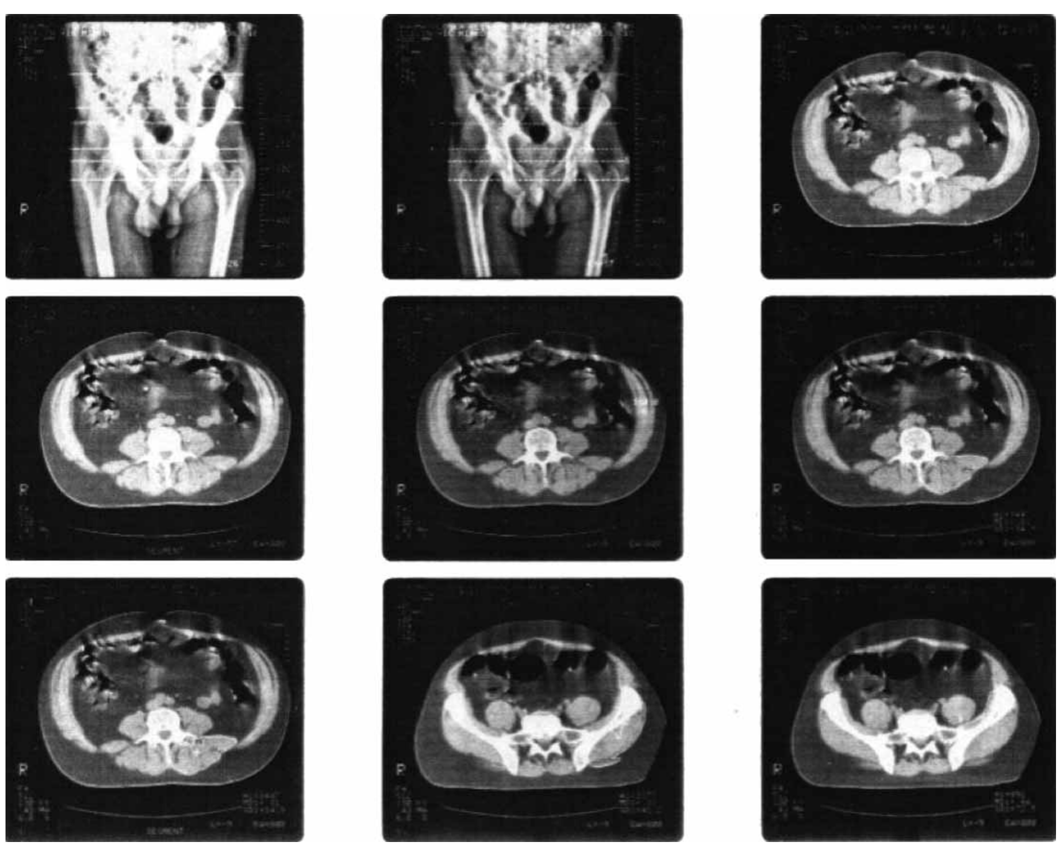

Fig. 1. Tomogram with marked levels of transverse pelvic cross-sections. Using CT, the cross-section of abdominal and gluteal muscles and of the iliopsoas muscle was determined as well as the distance between the muscle centroid and the bone.

The third slice depicts the acetabular roof. It shows the structure of the acetabular roof with compressed portion of the cancellous bone that corresponds to »the Pauwels eyebrow«, usually visible on x-rays of the hip. In acetebular fractures[15], the position of fragments is displayed. In addition to the large gluteal muscle, cross-sections of the middle and small gluteal muscles as well as of other pelvitrochanteric muscles, *m.iliopsoas*[16] and *rectus femoris* are shown (Figure 1). Only lower tendon portions of the straight abdominal muscle are shown in the group of abdominal muscles. The lower portion of the sacrum or coccyges are displayed at this level.

The next CT level passes through centers of both femoral heads. This slice shows the trochanter tips and almost all muscles inserting below the trochanter as well as the central acetabular portion with the acetabular fossa, bodies of the isciadic and pubic bone and a portion of the upper pubic branch. In case of acetabular fractures (Figure 2), several slices through the acetabulum are used in order to show three-dimensional reconstruction[17] of the acetabular image and the exact position of fracture fragments[18].

In any other position of the fracture gap, the minimum number of slices for approximate definition of the size and number of fracture fragments and gap is three slices with precisely defined distances.

The slice passing through the femoral head center allows more precise calculation of all distances, which simplifies the calculation of the moments of muscle forces and determination of static and dynamic loading of the hip joint[19] and acetabular roof. Below this level, another slice passing through the lower portion of the pelvis can be done to display the *ramus ossis ischii and ramus inferior ossis* pubis in the intertrochanteric region of the femur with all muscles of the femur and the lower pelvis.

The analysis of the size and direction of the resultant forces acting upon fracture fragments in case of iliac wing fractures shows the muscles forces that pull fragments laterally and posteriorly (Table 1). The analysis of the great gluteal muscle shows that the mean surface of the physiological cross-section is 58 cm^2. Based on the average length of measured muscles (17 cm) we calculated the mean volume of 604 cm^3. This muscle acts upon the external and internal portion of the iliac wings. The smallest force is the force of the *m. gluteus minimus* (on the average 348 N) and the largest of the *m. gluteus medius* (on the average 905N).

The muscle forces acting in the upward direction in case of iliac wing fractures are presented in Table 2. The largest force is produced by erector muscles, with the mean size of even 2.675 N. The second strongest muscle is *the m. obliquus externus* (on the average 840N).

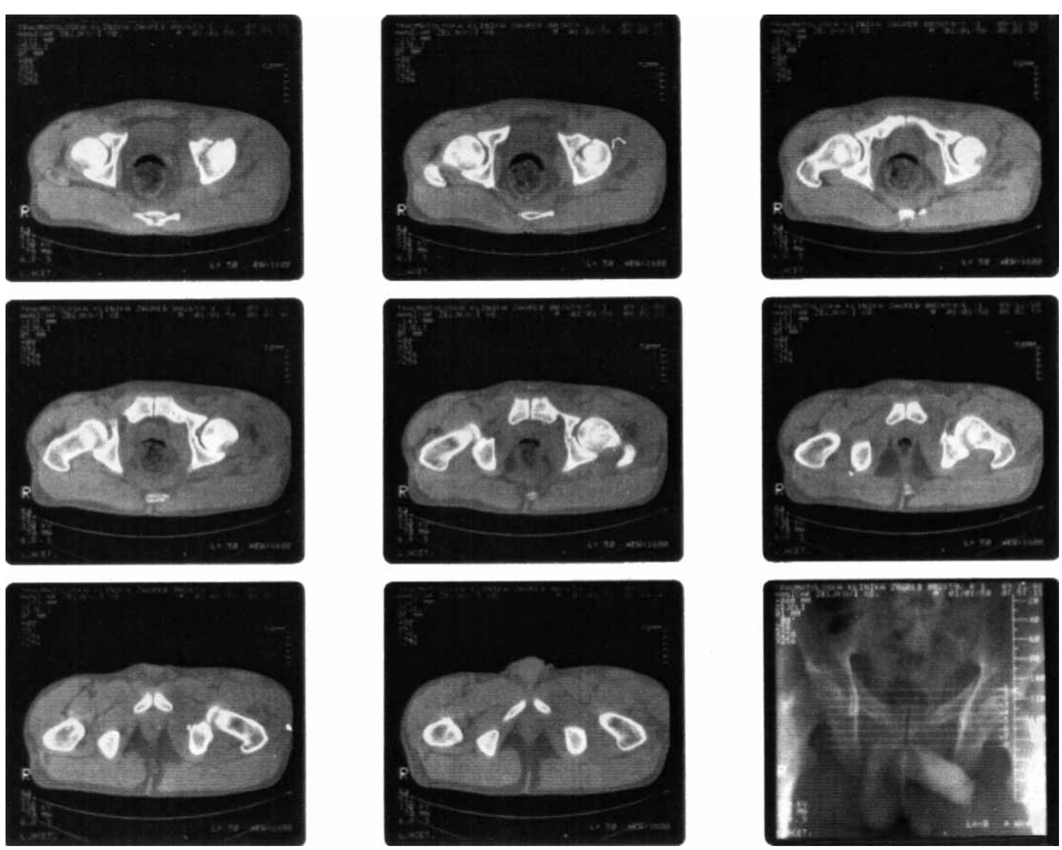

Fig. 2. Tomogram of the left acetabular fracture with pubic bone dislocation in the medial and downward direction (the effect of iliopsoas and inner obturator).

TABLE 1
MUSCLE FORCES IN ILIAC WING FRACTURES (ALA OSSIS ILII). MUSCLE FORCES PULL FRAGMENTS LATERALLY AND POSTERIORLY

Muscle	Anatomical cross-section A (cm^2)		Physiological cross-section FA (cm^2)			Muscle lengthn L (cm)		Muscle volume V (cm^3)			Access angle of muscle fibers (°)	Max. muscle force F (N)			Hoy et al. F (N)
	min	max	min	max	$\bar{X}$	min	max	min	max	$\bar{X}$	$\bar{X}$	min	max	$\bar{X}$	
M. gluteus maximus	56	70	39	76	58	15	19	387	880	604	34	480	850	680	1798
M. gluteus medius	27	49	32	61	47	10	14	160	420	275	9.7	700	986	905	1876
M. gluteus minimus	14	22	16	28		8	10	68	157	107	12	258	500	348	810
M. tensor facsiae latae	3	8	4	8.5		14	17	25	76		2.5				240

Min – minimal value, max – maximal value, $\bar{X}$ – mean value

TABLE 2
MUSCLE FORCES ACTING UPON THE ILIAC WING IN THE UPWARD DIRECTION

Muscle	Anatomical cross-section A (cm ^{2})			Physiological cross-section FA (cm^2)			Muscle force F (N)	
	min	max	$\bar{X}$	min	max	$\bar{X}$	min	max
M. obliquus ext. abd.	5	15	10	5	14	9.4	280	840
M. obliquus int. abd.	5	14	10	4	12	8	240	730
M. transv. abdominis	1.5	4.5	2.5	2	5.5	3		
M. quadratus lumborum	6	8	6.1			6	80	230
Erector muscles	18	27	22.5	15	24	20	1.35	4.00

Min – minimal value, max – maximal value, $\bar{X}$ – mean value

Muscles that pull fragments of the iliac wing in the anterior, medial and distal direction are the *m. iliopsoas* (range 640–1.474 N, mean 926 N), *m. rectus femoris* (mean 577 N), *m. iliacus* (498 N) and *m. sartorius* (124 N) (Table 3).

Two main forces act in case of pubic fractures (Table 4): a large group of muscles exerting larger force directs fracture fragments downwards. Of eight muscles in this group, the strongest is the *m. adductor magnus* with the maximum force of 1.326 N, although the range is extremely great (106–1.326 N). Muscles directing fragments upwards are *m. rectus abdominis* with maximum force of 711 N and the *m. obliquus externus* with maximum force of 280 N.

As many as 9 muscles are responsible for directing fragments of ischiadic bone downwards (Table 5). *M. semitendinosus* stands out with the mean force of 2348 N. *M. semitendinosus* is the second strongest muscle with the mean force of 800–1200 N, whereas the magnitude of other muscle forces are significantly smaller. Table 1–5 present data obtained in our study by measuring tomographs of our patients supplemented with data obtained by Brand and Friedrich[6].

TABLE 3
MUSCLE FORCES ACTING UPON THE ILIAC WING IN THE FORWARD, MEDIAL AND DOWNWARD DIRECTION

Muscle	Anatomical cross-section A (cm ^{2})			Physiological cross-section FA (cm^2)			Access angle of muscle fibers (°)	Max. muscle force F (N)		
	min	max	$\bar{X}$	min	max	$\bar{X}$	$\bar{X}$	min	max	$\bar{X}$
M. iliacus	11	31		15	49	12	6.5	451	596	498
M. iliopsoas			40				7	640	1.474	926
M. sartorius	2.5	3		2.5	3		0			124
M. rectus femoris			16	10	43		5–14	300	930	577

Min – minimal value, max – maximal value, $\bar{X}$ –mean value

TABLE 4
MUSCLE FORCES ACTING IN PUBIC BONE FRACTURES (OS PUBIS)

Muscle	A (cm^2)		V (cm^3)		Alpha (0)	F (N)		Remarks
Upwards	min	max	min	max		min	max	
M. rectus abdominis	4	13				237	711	
M. obliquus ext.	3	4			0	238	280	
Downwards	min	max	min	max		min	max	
M. adductor magnus	39	698	250	670	0	106	1326	
M. adductor longus		23			3.6	320	840	only a part of the muscle
M. adductor brevis		17	50	124				
M. gracilis		4	103	188	3		129	
M. pectineus		9	13	65	0	23	212	
M. ilipsoas (by pressure)		49	130	500	5		474	
M. obt.ext.	2.5	5	8	24	7	30	50	
M. obt.int.	9	10	32	43	25	30	150	

Min – minimal value, max – maximal value

TABLE 5
MUSCLE FORCES ACTING IN ISCHIADIC FRACTURES (OS ISHII)

Muscle Downwards	A (cm^2)		Alpha (0)	force F (N)		Remarks
	min	max		min	max	
Biceps (long head)	20	29	23	800	1.200	
Semimembronosis					2.348	Hoy et al. (1990)
Semitendinosis				5	50	
Obt. ext.				30	140	
Obt. int.	2.5	5				
Quadr. femoris	9	10				
Gemellus sup.		20		3	20	
Gemellus inf.	1.5	2.5		3	20	
Glut. max.	2	3			680	Only a part of the muscle

Min – minimal value, max – maximal value

Discussion

Depending upon the position, insertion and size of muscles, various forces act on each fragment of the fractured pelvis. Their interplay is very complex but it can be calculated using computer calculation programs. Apart from muscle forces, there are also forces of stabilization and the intrabdominal pressure.

In the process of fixation and stabilization of fractures favorable effects of stabilization forces should be used in order to make such a fixation strong enough to withstand muscle forces that tend to move the fracture fragments apart.

A correct pelvic classification is in most cases achieved by conventional radiography, but CT adds data regarding acetabular fracture and involvement of the posterior part of the pelvic ring as well as detection of intra-articular fragemnts and lesions of the femoral head[20,21]. When comparing total effective radiation dose of spiral CT and conventional 5-projection radiography of the pelvis with regard to the fracture classification, it has been shown that it is lower in spiral CT (4.4 *vs.* 5.0 mSv)[22]. Three-dimensional CT images help understand the precise position of the fracture gap, the degree of disruption of the articular surface and spatial relationships of fragments[23,24] but it is not a substitute for a good quality plain radiography and CT, since fracture lines demonstrated on plain radiography and axial CT scan are not always apparent on 3D CT scans[25]. New imaging techniques of pelvic fractures, such as stereoscopic 3D CT and computer generated 3D CT modeling are available in the world[26–28]. However, in our institution only plain radiography and CT imaging are routinely used in pelvic fracture evaluation.

Computer tomography of pelvic fractures allows measuring of cross-section surface of muscles and evaluation of lines and direction as well magnitude of muscle forces acting upon certain fragments. Our data correspond to data from the relevant literature obtained by analyzing cadaver material and calculation models[29–31]. By comparing the results we obtained in our study it is possible to show complex relationships of bones and muscles in pelvic fractures. Apart from muscle forces, forces of gravitation, static and dynamic forces and forces of inertia act in pelvic fractures.

Abdominal muscles attached[32] to the iliac crest act upon the iliac wings. These muscles are: *m. obliquus externus abdominis, m. obliquus internus abdominis, m. transverses abdominis* and at the back *m. quadratus abdominis*. The force of these muscles[33] that pull hip bone upwards is not equal to their maximum force, which is proportional to the physiological cross-section, but it corresponds to the resultant of the forces of all mentioned muscles. On the other hand, intraabdominal pressure should not be underestimated since it is also the result of several factors, because these muscles are a part of the so called »abdominal press« and play an important role. The action of *m. rectus abdominis*[34], which despite its insertion at the pubic bone, also acts upon the iliac wing via intraabdominal pressure. The posterior portion of the iliac wing is affected partly by the massive erector muscle that depending upon the site and shape of fracture gap, may participate in displacement of fracture fragments or even approximation and together with the SI and iliolumbar ligaments may contribute to stabilization of fracture fragments. All three gluteal muscles[35] and the *m. tensor fascia lata* have insertions on the outer side of the hip bone. These powerful muscles pull the fragment of the iliac wing in the lateral or lateral and posterior direction. The origin of the *m. iliacus* is located on the inner side of the iliac wing and the *m. sartorius* originates on the anterior side of the *spina iliaca anterior superior.* The body of the hip bone with the bearing portion of the acetabulum leans on the femoral head in the hip joint. Thus, loading forces of the body[36,37] (forces of gravitation and moments of forces) are transmitted onto the lower extremities. The moment arm of this force acting upon the hip joint at rest and during standing on both feet reaches the medial plane. During standing on one foot the center is shifted and the moment arm is extended to the opposite side. In this way the loading of the acetabular roof is increased. This moment arm is counterbalanced[38] by the forces of the following muscles: abductor muscles, all gluteal muscles and tensor m. of *fascia lata*. The moment of the counterbalance force is equal to the moment of gravitational force of the body but the pressure onto the acetabular roof is the resultant of both moments. The pubic bone[39] is pulled upwards and medially by the *m. rectus abdominis* and *m. pyramidalis*. Tendon of the *m. rectus abdominis* is split into two parts so that both *m. abdominis rectus* affect both sides of the pubic bone. The tendon attached to the opposite side of the symphysis pulls that side along with the ligaments and fixes the symphysis. Over the *ramus superior ossis pubis*, the end part of the iliopsoas muscle[40] is bent and is attached to the lesser trochanter. It exerts a significant pressure onto the pubic bone. The origin of medial femoral muscles is on the lower side of the pubic bone and their force acts downwards and laterally. Besides complex interplay of forces acting upon the pubic bone, obturator muscles also have influence in this area in addition to the action of muscles of the urogenital diaphragm that together with connective parts of the diaphragm prevent separation of the symphisis and medial portions of the pubic bone. The ischiadic bone exerts pressure on the surface during sitting or lying and is influenced by gravitation. This bone is fixed by the sacrotuberal and ischiofemoral ligamenst that participate in the transmission of drawing forces, although they are considered to be passive elements of the musculoskeletal system. Active muscle forces directed downwards result from the action of the *m. caput longum*, *m. bicipitis femoris* and *m. semimembranosus* and *m. semitendinosus*. These are long and powerful muscles, the extensors of the hip joint and flexors of the knee joint. This should be borne in mind since movements in the knee joint influence the interplay of the forces in the ischiadic bone. Pelvitrochanteric muscles may exert a direct and m. piriformis[41] with a portion of the *m. gluteus maximus*[42] an indirect lateral pressure on the ischiadic bone.

Conclusion

The method of CT proved to be highly suitable for three-dimensional definition[43] of fracture fragments. Physiological cross-section of muscles was calculated based on the measured length of muscles, calculated muscle volume and the measured length of muscle fibers. Apart from the data on the muscle strength[44], which is proportional to the physiological cross-section measured on tomograms, the analysis rendered data on the direction of muscle forces acting on fracture fragments.

Visualization of muscles that act upon fracture fragments[45] and determination of their forces along with understanding basic properties of allenthesis help in individual planning of fracture fixation that is stable enough to withstand all static and dynamic forces during the entire process of fracture healing, without fixation failure or implant breaking due to fatigue of the implanted material.

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ANALIZA MIŠIĆNIH SILA KOJI DJELUJU NA ULOMKE KOD ZDJELIČNIH PRIJELOMA

S A Ž E T A K

Kompjutorska tomografija korištena je u 50 odraslih ozljeđenika s prijelomima zdjelice u cilju određivanja veličine i položaja odgovarajućih mišića s obzirom na koštane elemente kako bi se izračunala veličina mišićnih sila koje djeluju na određene dijelove zdjeličnog prstena. Ovi su podaci poslužili za odabir optimalnog načina liječenja pojedinih ozljeđenika. Mjerena je dužina mišića, a izračunati volumen mišića je poslužio za izračun fiziološkog presjeka mišića. Izračunata je veličina i smjer mišićnih sila kod prijeloma crijevne, preponske, i sjedne kosti. To je učinjeno za sve mišiće kod različitih zdjeličnih prijeloma. Najjači mišić, koji djeluje u smjeru prema van i lateralno kod prijeloma crijevne kosti je *m. gluteus medius*. Najsnažnije povlačenje ulomaka kod prijeloma crijevne kosti u smjeru prema gore vrše mišići erektori, dok najsnažnije povlačenje u smjeru prema naprijed, medijalno i dolje vrši *m. iliopsoas*. Kod prijeloma preponske kosti, osam mišića povlači koštane ulomke prema dolje, a najjači od njih je *m. adductor magnus*. Samo dva mišića ih povlače prema gore: *m. rectus abdominis* i *m. obliquus externus*. Devet mišića je odgovorno za pomak koštanih ulomaka prema dolje kod prijeloma sjedne kosti, a najsnažniji je *m. semitendinosus*. Izračunavanje veličine mišićnih sila koje djeluju na koštane ulomke kod zdjeličnih prijeloma pomoću CT-snimki daje dodatne podatke za planiranje optimalnog operacijskog zbrinjavanja, koje za svaki pojedini prijelom osigurava stabilnu fiksaciju.