CLINICAL STUDY

Draft design of a rehabilitation aid for patients with acute painful fractures of vertebrae

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Abstract

Aim of the study: **To model the influence of abduction and adduction of the upper limb on the spinal load with the help of the laws of theoretical mechanics and the application of its results in clinical medicine.**
Biomechanical solution: **Biomechanical model of an upper limb is demonstrated as a construction consisting of a lever arm and a joint connection in articulation of the shoulder joint.** ***Conclusion:*** **Our application of results of the spine load modelling in relation to excess upper limbs load: A) designing a methodology of active therapy aimed at exercising upper limbs for osteoporotic patients, B) the application of basic principles of motoric activity in daily life, C) the draft design of a rehabilitation aid for patients with acute painful fractures of vertebrae in the thoracic area *(Fig. 5, Ref. 17)*.**
Key words: biomechanics, spine, upper limbs, vertebrae fractures, osteoporosis, rehabilitation.

A biomechanical model of the upper limb (UL) is demonstrated as a construction consisting of a lever arm and joint connection in articulatio humeri. The flexion in elbow and wrist was not considered in this task. The upper limb is connected to the trunk by the bones of shoulder girdle (ossa cinguli membri superioris: scapula et clavicula) in two different ways:

1) ventral – through acromion scapulae and clavicula to sternum. In this part the UL is connected to the rib cage by solid elements of the construction (bones),

2) dorsal – the solid construction of the UL is ended by shoulder blade bone and a further connection to the spine is provided by muscle groups (elastic elements of construction), which are attached to processi spinosi along the whole spine.

In creating this model we were interested primarily in the spinal load in relation to excess load (unloading) of the hands, and we simulated only the dorsal attachment of the UP to the spine.

The goal of the study

Modelling of the influence of the UL abduction and adduction on the spinal load using the laws of theoretical mechanics.

Application of the results

1) Setting up a methodology of motoric therapy for osteoporotic patients
2) Draft design of a rehabilitation aid for patients with acute vertebrae fractures

Biomechanical model: membrum superiorum at shoulder joint (1–3, 6–10).

Figure 1 shows a biomechanical model of the upper limb, shoulder girdle and spine. The UL is simulated as a lever with a joint connection in the point A (articulatio humeri).

The forces applied in the abducted UL are considered with regard to the point A. The point A_1 simulates the elbow, A_2 the wrist and A_3 is a final point of the arm length.

Individual segments on the UL (A-A_1, A_1-A_2, A_2-A_3) were selected to enable us to determine the centres of gravity T_1, T_2, T_3, i.e., the sites where the weight of individual segments of the UL is applied.

According to literary data (1) the shoulder mass is 2.8 %, the forearm mass 2.0 % and the hand mass 0.8 % of the total body mass in persons with normal values of body mass index (BMI).

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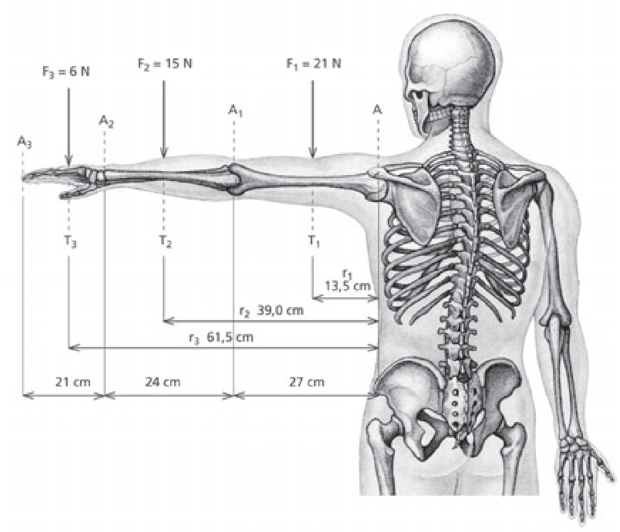

Fig. 1. Biomechanical model of abduced upper limb demonstrated as a construction of a lever arm and joint connection in the point A (articultio humeri or shoulder joint).

The values of distances among individual segments of the UL and the distance of shoulder joint from the spine (Fig. 1) we obtained by real measurements in a male:

mass: 74 kg; $F = m.g \quad g = 9.80665\ ms^{-2} \approx 10.0\ ms^{-2}$
height: 176 cm $F(mkgs^{-2} = N)$
age: 56 years
$A\text{-}A_1$=27 cm $A_1\text{-}A_2$=24 cm $A_2\text{-}A_3$=21 cm $A\text{-}A_3$=72 cm
r_1=13.5 cm r_2=39.0 cm r_3=61.5 cm

shoulder mass: $m_1 = 74.0 \dfrac{2.8}{100} = 2.07\ \text{kg} = 2.1\ kg$

forearm mass: $m_2 = 74.0 \dfrac{2.0}{100} = 1.48\ \text{kg} = 1.5\ kg$

hand mass: $m_3 = 74.0 \dfrac{0.8}{100} = 0.59\ \text{kg} = 0.6\ kg$

force of shoulder mass: $F_1 = m_1.g = 2.1.10.0 = 21$ N

force of forearm mass: $F_2 = m_2.g = 1.5.10.0 = 15$ N

force of hand mass: $F_3 = m_3.g = 0.6.10.0 = 6$ N

Forces F_1, F_2, F_3 are applied in the gravity centres T_1, T_2, T_3 (in the middle) of individual segments of the UL. The force F_1 is applied to the moment arm r_1, the force F_2 to the moment arm r_2, the force F_3 to the moment arm r_3.

The calculation of the resultant of forces in relation to the shoulder joint A (Fig. 2) (2, 3, 7, 8)

The resultant force R equals the sum of individual forces F_1, F_2, F_3 applied to the shoulder joint.

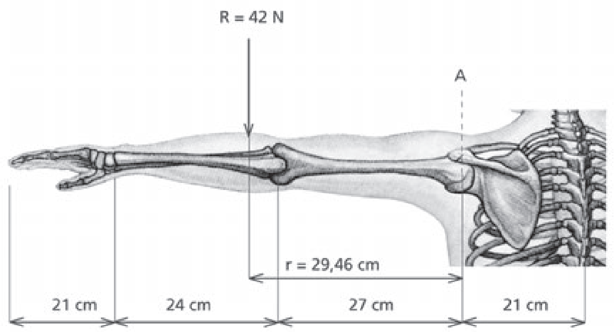

Fig. 2. The resultant force (R) and position (r) of individual forces F_1, F_2, F_3 of upper limb are applied in relation to the shoulder joint.

$R = F_1 + F_2 + F_3 = 21 + 15 + 6 = 42$ N

The length of the moment arm can be calculated from the equality condition of the moments of forces F_1, F_2, F_3 and moment of resultant force R to the point A applied to the UL.

$R.r = F_1.r_1 + F_2.r_2 + F_3.r_3 = 29.46$ cm

$$r = \frac{F_1.r_1 + F_2.r_2 + F_3.r_3}{R} = \frac{283.5+585.0+369.0}{42} = 29.46 \text{ cm}$$

Figure 2 shows the length of the moment arm r, upon which the resultant forces of the UL mass are applied in relation to the shoulder joint.

Static modelling of abducted UL and shoulder joint in the point A (Fig. 3)

The radius of the humeral head (caput humeri) is 3 cm long (4). It is the distance from the rotation axis of the humeral head to its edge (AB). From the aspect of theoretical mechanics this radius is a lever arm, upon which the A point from one side the resultant of the UL forces on the moment arm. *r* is applied on one side, and, on the other side at the B point the reaction force originating in the musculature of mm. humeri is applied to the moment arm *a.* The B point simulates the site of insertions of mm. humeri, because the muscles of mm. humeri (except m. deltoideus) are attached to the epiphysis proximalis in the vicinity of caput humeri.

Insertions of muscles of mm. humeri in the area of epiphysis proximalis:

m. supraspinatus .... tuberculum majus humeri
m. infraspinatus .... tuberculum majus humeri
m. teres minor .... tuberculum majus humeri
m. teres major .... crista tuberculi minoris
m. subscapilaris .... tuberculum minus humeri

The insertion of m. deltoideus is in the area of corpus humeri:
m. deltoideus .... tuberositas deltoidea humeri

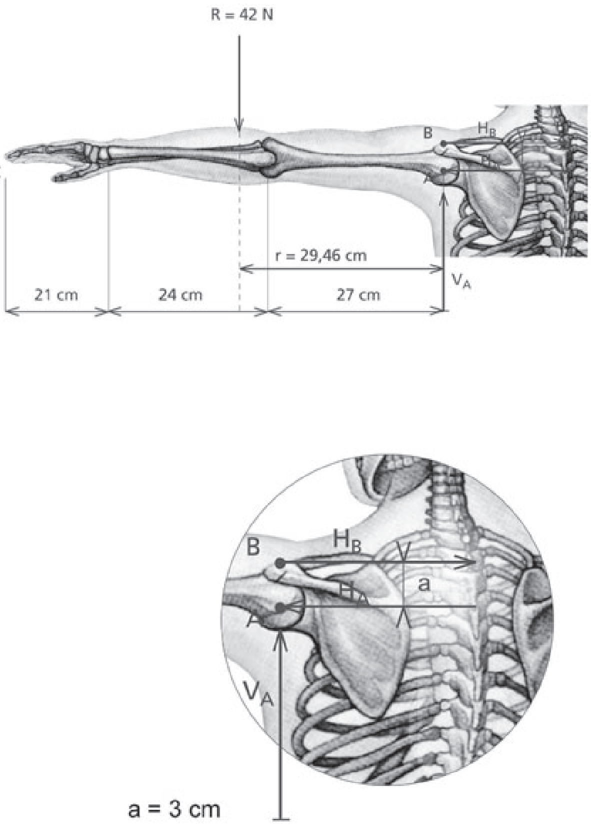

Fig. 3. The effect of an abducted upper limb on the shoulder joint.

The muscles of mm. humeri cooperate in each movement of the UL, while the prevailing role in the abduction of the UL is played by m. deltoideus and m. subscapularis. Reaction forces generated in mm. humeri during the abduction of the UL are transferred through mm. spinohumorales to the spine.

We assumed that the abducted UL are in the same plane, then out of the three conditions of the balance of plane system of forces we determined the reaction forces in muscle insertions (B) and in shoulder joint (A), which are transferred as action forces to a relevant segment of thoracal spine. If the UL is to be maintained in abducted position, it is necessary to meet these three conditions for the balance of forces acting in the plane.

Three static conditions of the balance of the plane system of forces in the theoretical mechanics (2, 3, 4)

1) the sum of vertical forces in the plane equals zero
2) the sum of horizontal forces in the plane equals zero
3) the sum of moments of forces for a given point equals zero

Figure 3 shows three attachments securing the balance of forces in abducted UL. Two attachments HA and HB are formed by muscle insertions and muscle fibres of mm. humeri and the attachment VA is simulated by the support of the articular head of humerus in the socket of the scapula.

This support prevents the joint head from shifting in the vertical direction. The three attachments HA, HB, VA do not intersect in one point and so the condition of form specificity is observed. Correct selection of attachment directions guarantees the form specificity of the UL in the plane.

Reactions to the load of the weight of abducted UL upon the shoulder joint are generated in the attachments HA, HB, and VA. These reactions can be determined from the three conditions of balance, and are valid for the state of balance of the abovementioned forces acting in the plane.

To solve the equations we chose two moment conditions and one condition of vertical forces balance.

1) $\mathbf{\Sigma M_A = 0}$ the sum of the moments of forces applied to the point A equals zero
2) $\mathbf{\Sigma M_B = 0}$ the sum of the moments of forces applied to the point B equals zero
3) $\mathbf{\Sigma V = 0}$ the sum of vertical forces in the plane equals zero

Application of the three conditions of the balance of forces applied in the plane, which were used in the solution of biomechanical model demonstrating the load of shoulder and mm. humeri by the abducted UL.

1) The sum of the moments of forces applied to the point A equals zero

To meet the condition of balance in the shoulder joint, i.e., in the point A, it stands that the magnitude of the moment of the reaction force in the muscles H_B (mm. humeri) applied to the moment arm *a* equals the moment of the resultant R (i.e., the weight of the UL) applied to the moment arm *r*.

The moment of force is defined as the magnitude of the force F applied to the moment arm <u>*a*</u> (M = F.a).

Explanation of symbols used in equations.

According to the convention the moment of a force applied clockwise is called a negative moment and is marked by the symbol of minus (-), the moment of force, applied anticlockwise is called a positive moment and is marked by the symbol of plus (+). The magnitude of reaction muscular force HB is calculated from the first moment condition of balance:

$$\Sigma M_A = 0 \qquad -H_B.a + R.r = 0 \qquad H_B = \frac{R.r}{a} = \frac{(42\,.\,29.46)}{3} = 412.44\ \mathrm{N}$$

Within the attachment H_B a reaction force is generated to the load by the weight of the UL of the magnitude of 412,44 N.

2) The sum of the moments of forces applied to the point B equals zero

The consideration is the same as for the point A. The magnitude of the reaction force in the muscles H_A applied to the moment arm *a* equals the magnitude of the resultant R applied to the moment arm *r*. The moment of reaction muscular force equals

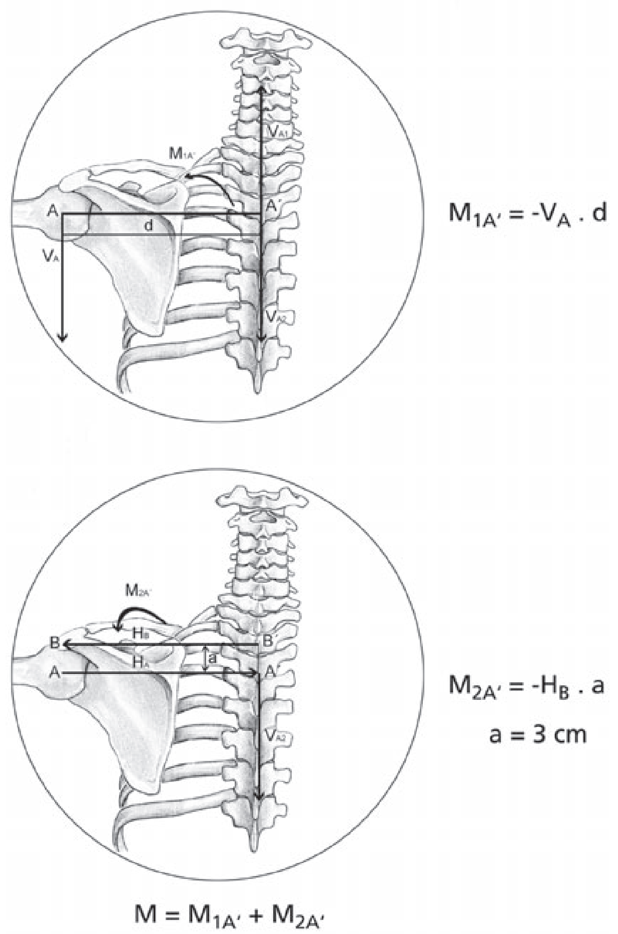

Fig. 4a, 4b. The transfer of forces from the shoulder joint into the spine in an abducted upper limb.

the moment of resultant force of the UL mass. The magnitude of reaction muscular force H_A is calculated from the second moment condition of the balance:

$$\Sigma M_B = 0 \quad -H_A.a + R.r = 0 \quad H_A = \frac{R.r}{a} = \frac{(42\ .\ 29.46)}{3} = 412.44\ N$$

Within the attachment H_A a reaction force is generated to the load by the weight of the UL of the magnitude of 412.44 N and it is of an opposite sense as the reaction force in the attachment H_B.

3) The sum of vertical forces in the plane equals zero

If the condition holds that the sum of vertical forces in the plane equals zero, then there is a correct assumption that in the point A the vertical force R is countered by an equally large vertical force V_A generated in the bone of the scapula socket, but of opposite sense. The force V_A is calculated from the condition of the balance of vertical forces:

$$\Sigma V = 0 \qquad +V_A - R = 0 \qquad V_A = R = 42\ N$$

Within the attachment V_A a vertical reaction force is generated to the load by the weight of the UL of the magnitude of 42 N.

The transfer of forces from the shoulder joint into the spine in abducted UL (Fig. 4a, 4b) (3–8, 10–12)

Reaction forces H_A, H_B, V_A generated during the load of the left shoulder joint by the weight of the abducted UL are applied to the spine through mm. spinohumerales as the so-called action forces, which are of the same magnitude but of opposite sense. This is the so-called equivalent forces system of the actions of shoulder joint upon the spine. The force H_B is transferred into the spine as a horizontal tensile force (point B'), the force H_A as a horizontal compressive force (point A'), and the force V_A as a vertical compressive force.

(In accordance with the convention the compressive force is marked by the symbol of minus (-), the tensile force by plus (+).

(Fig. 4a)

For the vertical force V_A two equally strong forces V_{A1} and V_{A2} are considered in the spine (balanced system of forces).

These two forces have a common application point of A', they are of the same magnitude and act in the same arc; however, they are of the opposite sense.

The forces V_A and V_{A1} generate a positive bending moment of force on the moment arm <u>*d*</u>. The relation of the moment of the force V_A to the point A':

$\mathbf{M_{1A'}} = V_A.d = 42.21 = 882$ Ncm

The vertical force V_A stresses the spine by the moment of force to the point A'($M_{1A'}$) and by compressive vertical force $\mathbf{V_{A2}}$ (-42 N).

(Fig. 4 b)

The horizontal force H_A is applied in relation to the point A' upon the moment arm r = 0, it does not generate any force moment

The horizontal force H_B generates in relation to the point A' on the moment arm *a* a force moment $M_{2A'}$:

$M_{2A'} = H_B.a = 412.44.3 = 1237.32$ Ncm

Resulting moment of forces (M) applied upon the spine during the abduction of one UL equals the sum of both moments:

$M = M_{1A}' + M_{2A}' = (V_A.d) + (H_B.a) = 882 + 1237.32 = 2119.32$ Ncm

During *the abduction of one UL* the spine is stressed by the sum of the moments of forces $M_{1A'}$ and $M_{2A'}$ (2119.32 N cm) and by the compressive vertical force V_{A2} (-42 N).

During *the abduction of both UL* the moments of forces $M_{1A'}$ (l.dx.) and $M_{1A'}$ (l.sin.), $M_{2A'}$ (l.dx.) and $M_{2A'}$ (l.sin.) are in the balance, because they are of the same magnitude, are of the opposite sense and have a common application point A', B' and their static effect does not manifest on the soluble system.

Vertical compressive forces V_{A1}(l.dx) and V_{A1} (l.sin) are added up together in case of *the abduction of both UL*:

$$V_{A1}(l.dx) + V_{A1}(l.sin) = (-42) + (-42) = -84\ N$$

The results of the calculation of forces applied upon the spine show that during *the abduction of both UL* the spine is stresses only by the sum of two vertical compressive forces of the 84 N magnitude, in contrast *to the abduction of only one UL*, when the spine is submitted to an unfavourable action of the sum of bending moments of forces ($M_{1A'}+M_{2A'}$) of the magnitude M = 2119,32 N cm as well as vertical compressive force V_{A2} of -42 N magnitude.

In the *adduction of one UL* the gravity of the UL generates a reaction vertical force V_A (-42 N) in the shoulder joint (A), but it does not generate in the joint horizontal reaction forces H_A and H_B as in the abduction of the UL, because the moment arm r equals zero. Reaction force V_A is transferred through mm. spinohumerales upon the spine as an action force, which is of the same magnitude but of the opposite sense. The force V_A and the force V_{A1} generate a positive bending moment on the moment arm d (Fig. 4 a). The moment of force V_A in relation to the point A' equals:

$$M_{A'} = V_A.d = 42.21 = 882\ Ncm$$

Reaction vertical force V_A generated in the shoulder joint is applied upon the spine by the moment of force to the point A' ($M_{A'}$ = 882 Ncm) and by the compressive vertical force V_{A2} (-42 N).

In *the adduction of both UL* vertical compressive forces V_{A2} (l.dx.) and V_{A2} (l.sin.) are added up together in the same way as in the abduction of both UL:

$$V_{A2}(l.dx.) + V_{A2}(l.sin.) = (-42) + (-42) = -84\ N$$

In *the abduction* or *adduction of both UL* the spine is stressed at the same level, namely by the sum of two vertical compressive forces V_{A2}.

Application of the results of spinal load modelling in relation to the excess load of hands.

A) setting up a methodology of motoric therapy focused on exercising upper limbs in osteoporotic patients and patients with osteoporotic vertebral fracture:

1) to exercise symmetrically with both UL,
2) in the set of exercises to exclude:
   a) dynamic strengthening exercises with dumbbells,
   b) dynamic strengthening of one UL with rubber band (one end of the rubber band is fixed and the patient is stretching the other end by the UL),
3) to exclude sports straining asymmetrically only one UL (tennis, handball, volleyball, etc.).

Dumbbell exercises are not suitable either in symmetric exercise with both UL or in isolated strengthening of one UL. In the symmetrical exercise with both UL there is an increase of the vertical compressive force upon the mechanically weakened spine in the magnitude of the sum of masses of both dumbbells. In exercises with one UL there is an increase of the magnitude of bending moment of force applied to the spine as well as an increase of the vertical compressive force upon the spine. The bending moment as well as vertical compressive force are increased by the weight of the dumbbell. Strengthening of one UL with a dumbbell and lifting weights by one UL represent the most unfavourable load of the spine in UL motoric activity.

B) application of basic principles of motoric activity in daily routine:

a) to avoid carrying and lifting heavy weights, always to carry and lift light weights with both hands,
b) when shopping, always use shopping trolleys, do not carry shopping bags in one hand,
c) osteoporotic patients should always sit down in public transport, when they stand and hold themselves by one hand, the impact force in case of sudden braking is unfavourably transferred to the spine and by a low BMD it could cause a vertebrae fracture.

C) Draft design of a rehabilitation aid for patients with acute painful vertebrae fractures in thoracic area (Fig. 5a, 5b).

The purpose of the proposed rehabilitation aid.

Osteoporotic vertebrae fractures are mostly accompanied by an intensive pain syndrome, comprising the pain of the fractured vertebra (damaged nerve fibres in periosta, in pars trabecularis and in pars corticalis) and the muscular pain (ischemia).

Wedge-shaped deformations of vertebrae and the most explicit curvature of the spine are caused by the fractures of those vertebrae which are placed in the peaks of physiological curvature of the spine in Th and LS areas. Intervertebral and flat spinal muscles surrounding a fractured vertebra are suddenly exposed to strong tensile forces resulting from a new pathological configuration of the spine, causing the ischemisation of muscles and consequently their myalgia. Muscles are not adapted to the new pathological curvature of the spine and significantly share in the pain syndrome in acute vertebrae fractures. Any motoric activity of the UL increases the pain of the spine, as the UL generate tensile forces in mm. spinohumerales (especially m. latissimus dorsi, m. rhomboideus minor et major, m. deltoideus) and simultaneously, through these muscles attached to processi spinosi along the whole spine they stress the spine by bending moments of forces and vertical compressive forces in Th area. Acute myalgia often turns into a chronic state and persists even after the vertebra fracture is healed. It requires a long-term complex therapy (both medicamentous and non-medicamentous) (13–17).

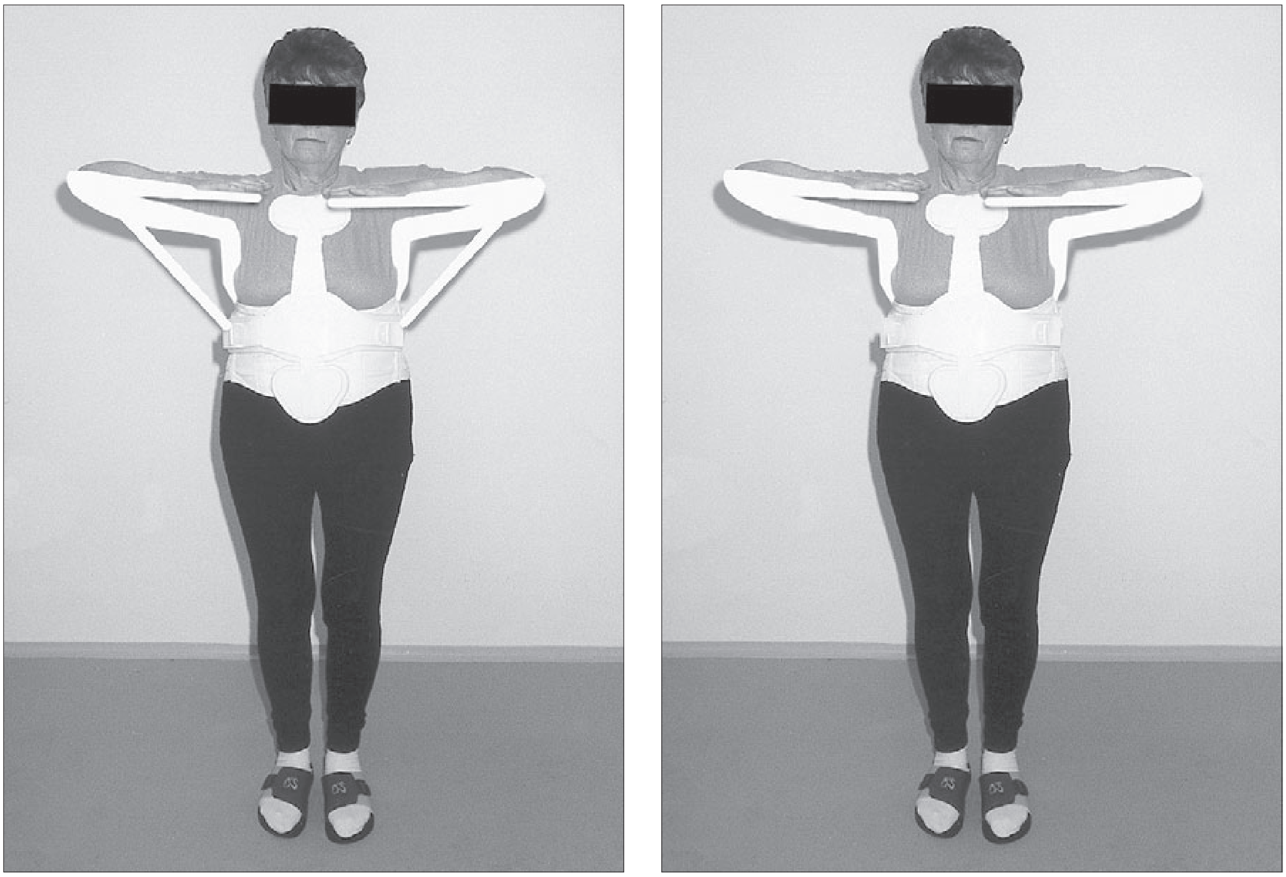

Fig. 5a, 5b. Draft design of the rehabilitation aid for patients with acute vertebrae fractures. a) with underarm fixed bearing, b) without underarm fixed bearing.

Biomechanical principle of utilising the proposed rehabilitation aid

As a part of complex therapy we propose a rehabilitation aid which should decrease the tensile force in ischemic muscles of the spine in Th area and eliminate the vertical compressive force upon the spine area caused by the weight of the UL. The rehabilitation aid would transfer the vertical compressive force from the spine to ala ossis ilii. The purpose of the rehabilitation aid is to unload the spine from the weight of both UL.

Intermittent unloading of spinal musculature by the weight of both hands (intermittent wearing the rehabilitation aid) would result in gradual adaptation of the spinal musculature to the newly formed permanent pathological curvature of the spine, i.e., to a permanent stress by bigger tensile forces and, simultaneously, the vertical compressive force upon the fractured vertebra (e) in Th (LS) area would be diminished by the weight of UL. During the unloading of the spine and spinal musculature by the weight of the hands:

a) there is an improved blood supply of the musculature (elimination of ischemia), which is a condition for the decrease of myalgia intensity in acute stage,
b) a lesser pressure is applied upon nerve fibres in periosta pars corticalis and trabecularis of the fractured vertebra.

Description of the construction of proposed rehabilitation aid

Figure 5 shows the rehabilitation aid we propose to use in patients with acute painful vertebrae fractures in thoracic area during the fracture healing stage (4–6 weeks).

The rehabilitation aid consists of a corset (classic constructed corset with three supporting points, which prevent the flexion of the spine: sternumbasis, symphysis pubica, lumbo-sacral region) and two support consoles attached in side parts of the corset. Horizontal level of the consoles has to be in the level of the shoulder joint, so the whole weight of the UL should be transferred to consoles. The consoles are formed by metallic skeletons from a light metal embedded in plastic. The consoles acquire so a form of a groove, its inner side lined with a cotton textile.

Benefits of the proposed aid

a) using the proposed aid would lower the costs of medicamentous therapy (analgesics, NSAR, myorelaxants, opiates) in the acute fracture stage,
b) gradual adaptation of the spinal musculature in the stage of acute fracture using the proposed rehabilitation aid and

targeted motoric therapy focused at strengthening the spinal musculature started after the healing of the fracture would decrease the incidence of chronic myalgias (persisting in most patients following the vertebrae fractures) and in doing so lowering the costs of long-time medicamentous therapy of chronic pain,

c) the aid could be used also in patients after traumatic vertebrae fractures.

(Notice: All figures are original created by author.)

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Received September 21, 2005.
Accepted October 27, 2005.