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BIOMECHANICS OF HAND

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Summary: *The top of article is mechanic model of hand power grip. The algorithm of calculation of tendon and finger joint forces and finger stress state is presented. The results can be used as loading for finger implants. The mechanic model consists of tendons and stiff finger bone elements. The bending moments at joints and the friction of tendons at vaginas are omitted. The tendon influence is searched as a rope in pulley system. The power grip of object is solved in two forms: a grip of some object, for example pliers and a grip of a bar with circle cross-section, for example if a man hangs on a horizontal cross bar. The algorithm was interpreted on a computer. The program can be used for pathologic cases too if some fingers don't operate or have pathologic form.*

1. Introduction

The biomechanics model of hand power grip is solved. The task is solving of geometry position of finger links, stress state at link bones and tendon forces if the object is griped with given force. The aim of research was the completing of a computer program which enables for given anatomic hand form and the size of an object to calculate bone stress state and tendon force values. The stress state can be calculated for healthy hand. The pathologic case can be solved only if the hand hasn't some fingers or some finger links don't be able operate.

The calculation algorithm is developed for two cases of power grip of an object. The 1st variant is the power grip of some object between nth finger links and wrist. The hand has to grip the greater object between the last finger links and wrist and the small object can be griped with the greater force if it is put moor deeply into the palm, it means the object is griped with the greater force between the 3rd (n=3) or the 2nd (n=2) finger link and wrist. The parameter *n* is input value of program. The hand geometry is searched, it means the finger links position and their slopes is calculated. The input parameter is the size of griped object only.

The 2nd variant is a power grip of the round post, for example a man hanging at a horizontal bar. The hand position is elected to be a wrist (ossa carpi) on the vertical under the bar center and the hand has contact points with the bar at the surface of link centers.

The grip force is an input parameter. The both cases suppose that the healthy fingers without a thumb are in activity. The thumb only secures the hand not to slip out of an object.

The length of finger links makes Fiboracci order. The length is a sum of previous two lengths (from the end) in this order, for example 18, 28, 46, 74 [mm]. The variant according to Hoggard commend considers the link length as 1,618 time previous length. Thompson [2] shows the form of flexed finger too.

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Batmanabane and Malathi (1985) have published the maximums of angles of flexed linger at its joints, they are (from end of finger) 90^o (little finger 95^o), 100^o, 110^o and 90^o. The angles are smaller if only one finger is flexed. The slope angles can be greater if it is pushed on the finger. Doyle and Blythe (1998), Strickeland (1987) present the fixation of tendon vagines on palmar part of hand. The flexor is considered according to Brand (1985, 1993). The flexor is at tendon vagina which has the same form as finger bones and near at joints has arch form with radius *r* and the shortness during the flexion is αr, where α is bending angle at the joint. The same displacement is at extensor. Verdan (1979) and Strickland (1987) declared that the movements are at extensor vaginas 3, 16, 44, 55 [mm] and at flexors 5, 16-17, 26-23, 46-38, 88-85 [mm]. The curvature radius depends on the ligament state. The biomechanics of hand is based by Mc Brida (1942), Griffiths (1943), Napier (1956) and Lansmeer (1963). Napier divides two hand grips: power grip and precision grip. The finger is flexed at joint by the flexor tendon force at distances *r*= 5, 7.5, 10, 12.5 [mm] start from radio-carpal connection for the finger length 200 mm (Brand (1993)). The values must be corrected by the finger length measuring.

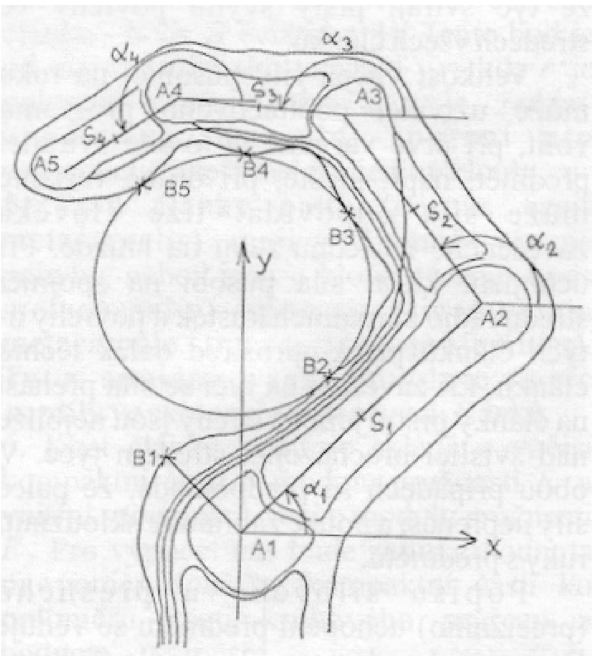


Fig. 1. Schema of the hand links and tendons.

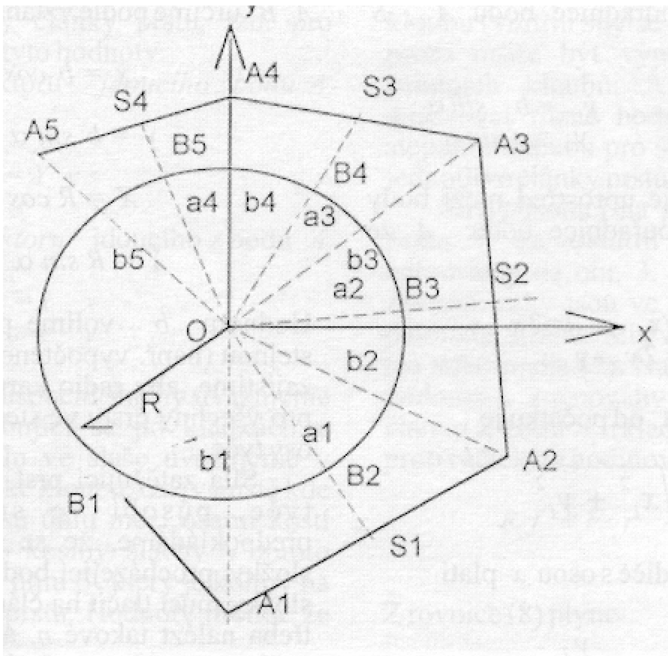


Fig. 2. Geometry of power grip of horizontal bar.

2. Calculation presumption and used parameter

The following algorithm supposes this simplification:

1. The object is griped by 4 fingers with 4 links and the trump doesn't work. The trump stress state isn't study. The fingers will be numbered 1, 2, 3, 4 from forefinger to little finger and the finger links 1, 2, 3, 4 from wrist (corpus ossis metacarpalis has number 1).

2. The finger links (and wrist) are connected by joints which don't transmit bending moments. The mechanical system of the hand considers stiff bones (bone deformation is neglected) and the ideal bending tendons. The flexors bend the fingers and they are situated on the palmar site of the hand, each finger link has its own flexor. The tendons are in the tendon vaginas (vaginae synoviales), which is support near joints by ligaments (vaginae fibrosae digitorum manus). The

friction of tendons at vaginas is omitted. The distance between the flexors at i^{th} joint from this joint is marked f_i. The tendons and their vaginas are partly linear and curved and they are solved as system of cables and pulleys which is fixed to the joints. The tendon force bends the finger with the moment which is equal force times the distance f_{ij}.

3. The finger links have circle cross-sections with the minimum of diameter at its center of length.

4. The finger link touches of the object at point B_i which has the distances from bone center νr, where r is bone radius and ν is input parameter.

5. The wrist (carpus) is solved as one joint. The 1st finger links (ossa metacarpi) moving are bounded because they are connected by ligaments. The connection enables small differences at the 1st link slopes (cylindrical form of wrist).

6. The finger bones have compact surface layer with elastic module E_1 and spongiest part with module E_2.

The schema of hand griping the object is at the fig. 1, the follow parameters is used:

$A_1(x_1,y_1),\ldots, A_5(x_5,y_5)$ … joints (begins and ends of finger links), correctly centers of mutual rotation of links.

$B_1(X_1,Y_1),\ldots, B_5(X_5,Y_5)$ … contact points of finger links and object, they are at centers of links

S_1 $(x_{s1},y_{s1}),\ldots, S_4(x_4,y_4)$ … centers of finger link bones

$\alpha_1,\ldots, \alpha_4$ … slope angles of finger links

β, γ … assistant angles

$L_1,\ldots, L_4$ … lengths of finger links

$r_1,\ldots,r_4$ … finger link radiuses

R … diameter of griped object

ν … parameter which defines relationship of distance between finger surface and bone axis and bone radius

f_i … distance flexors from the i^{th} joint

3. Geometry of power grip of object

The coordinates of points A_i can be calculated from

$$\begin{aligned} x_{i+1} &= x_i + L_i \cos\alpha_i \\ y_{i+1} &= y_i + L_i \sin\alpha_i \end{aligned} \tag{1}$$

where α_i are the slope angles of i^{th} finger link (see fig. 1) and L_i is its length (distance between turning centers).

The positions of the points B_i are

$$\begin{aligned} &X_1 = -r_1\nu\frac{y_2}{L_1}, Y_1 = r_1\nu\frac{x_2}{L_1} \\ &X_{i+1} = \frac{x_i + x_{i+1}}{2} - r_i\nu\frac{y_{i+1} - y_i}{L_i}, Y_{i+1} = \frac{y_i + y_{i+1}}{2} + r_i\nu\frac{x_{i+1} - x_i}{L_i} \end{aligned} \tag{2}$$

r_i is bone radius and v is parameter which defines relationship of distance between finger surface and bone axis and bone radius.

Rotation angles α_i of bone links axis are

$$\begin{aligned} \alpha_2 &= \alpha_1 + \beta \\ \alpha_3 &= \alpha_1 + (1+k)\beta \\ \alpha 4 &= \alpha_1 + (1+1{,}5k)\beta \end{aligned} \tag{3}$$

where $\beta = \alpha_2 - \alpha_1$ is angle between the 1st and 2nd finger links. Angle β will be determined to be distance between B_2 a B_{n+1} equal to size of grip object d. The 1st approximation is $\alpha_1 = 0$, (the 1st finger link is horizontal).

The value of k is calculated to be for d=0 the points B_1 and B_{n+1} at the same place, it means that for their distance is valid

$$\begin{aligned} \Delta x &\equiv L_1 + L_2 \cos\alpha_2 + ... + \frac{L_n}{2}\cos\alpha_n - r_n v \sin\alpha_n = 0 \\ \Delta y &\equiv L_2 \sin\alpha_2 + ... + \frac{L_n}{2}\sin\alpha_n + r_n v \cos\alpha_n - r_{c,1} v = 0 \end{aligned} \tag{4}$$

If (3) is set to (4) we will have got a system of transcendent equations for the unknowns´ β, k.

Now the equations (4) (using formulas (33)) will be solved by Newton’s iteration method according to follow algorithm:

1. $k_1 = 0.5$, $\alpha_1 = 0$, $\beta_1 = \pi/2$

2. β_1 is increased till value Δy (see (4)) will be negative

3. The better estimate is calculated from

$$\begin{Bmatrix} \beta_{i+1} \\ k_{i+1} \end{Bmatrix} = \begin{Bmatrix} \beta_i \\ k_i \end{Bmatrix} - \begin{bmatrix} \dfrac{\delta\,\Delta x}{\delta\,\beta} & \dfrac{\delta\,\Delta x}{\delta\,k} \\ \dfrac{\delta\,\Delta y}{\delta\,\beta} & \dfrac{\delta\,\Delta y}{\delta\,k} \end{bmatrix} \begin{Bmatrix} \Delta x \\ \Delta y \end{Bmatrix}$$

The calculation according to point 3 is repeated till the calculation error is greater than given error.

The values β and k were calculated for object diameter equal 0 according to previous algorithm, now it must be changed β to be the distance between B_2 and B_{n+1} equal to the given object diameter R. The value k isn't changed and value β is calculated from follow algorithm:

1. $\alpha_1 = x_1 = y_1 = 0$, β, k are results from previous algorithm.

2. The values α_i, x_i, y_i, and X_i, Y_i are determined from formulas (1), (2), (3).

3. Distance of points B_2 and B_{n+1} is

$$c = \sqrt{X_{n+1}^2 + (Y_{n+1} - v r_1)^2}$$

4. If $\varepsilon = c - R < 0$ (the distance between the points B_2 and B_{n+1} is less than object diameter d) then

$$\beta_{old} = \beta, \quad \varepsilon_{old} = \varepsilon, \quad \beta = \beta - 0.1$$

and the algorithm continue from 2.

At the appositive case is continued from 5.

Comment: if $c<d$ for $\beta \le 0$, the task cannot be solved because the object diameter is too great for grip.

5. Now the correct value of angle β is at $\langle \beta, \beta_{old} \rangle$

The better estimate can be calculated with help Regula-Falsi method

$$\beta_{new} = \frac{\varepsilon\beta_{old} - \varepsilon_{old}\beta}{\varepsilon - \varepsilon_{old}}$$

The calculation is repeated till the value $|\varepsilon|$ is less then given occurrence.

The finger grip force F has direction from the point B_2 to the point B_{n+1}. The finger will be turn to be the force F (join of points B_2 and B_{n+1}) vertical. The turn angle can be calculated from

$$tg\alpha_1 = \frac{X_{n+1}}{Y_{n+1} - vr_1}$$

If the value Y_{n+1} - vr_1 is near to zero the finger turning isn't be provided. The other values $\alpha_2,...,\alpha_n$ are calculated from formulas (4).

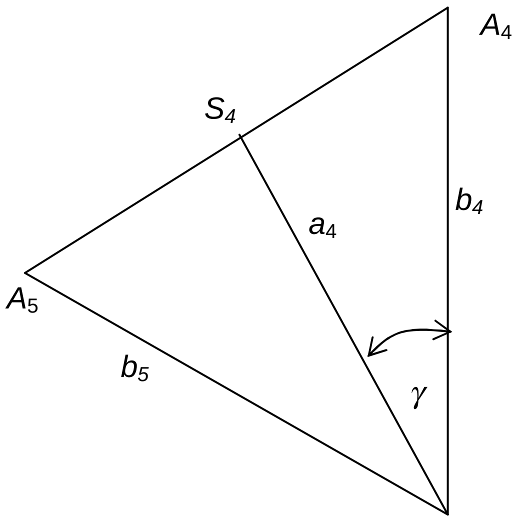
The previous algorithm is used for all fingers. The fingers have different positions of points A_i, B_i because the finger links lengths are different. The smaller finger has the greater angle α_1. The inference is cylindrical form of a wrist that corresponds with reality.

If the tong is griped the vertical force F loads the point B_{n+1}. The forces at the points B_i are zero except

$$F_{y,n+1}=F \qquad (6)$$

4. Geometry of power grip of round post

The example of a power grip of a round post is a man hanging at a horizontal bar. The geometry of finger position is at fig. 1 and 2. We presume that the finger and bar contact point is situated on the line between bar center and link center and the last finger link has this line perpendicular to bone axis.



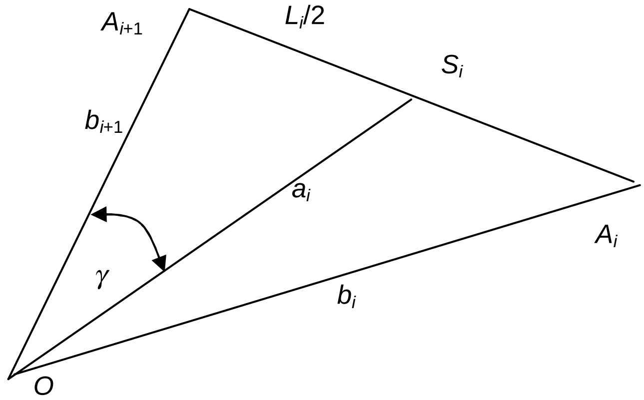


Fig. 3. Geometry of last finger link. Fig. 4. Geometry of 1st to n—1 finger links.

Distance between the bar center and link center is

$$a_i = R + r_i v$$

where R is bar radius, r_i is finger link radius at link center, v is relationship of distance between finger surface and bone axis to bone radius, vr_i is distance between S_i (center of finger link axis) and finger surface.

The angle of last bone axis can be calculated according to fig. 3

$$b_{n+1} = b_n = \sqrt{a_n^2 + \frac{L_n^2}{4}}, \qquad tg\gamma = \frac{L_n}{2a_n}$$

The angles b_n, a_n, b_{n+1} with x axis are

$$\beta_{b,n} = \pi/2, \;\; \beta_{a,n} = \beta_{b,n} + \gamma, \;\; \beta_{b,n+1} = \beta_{a,n} + \gamma$$

A_n is situated on y axis. Coordinates of A_n, A_{n+1} is

$$x_n = 0, \;\; y_n = b_n, \; x_{n+1} = b_{n+1}\cos\beta_{n+1}, \; y_{n+1} = b_{n+1}\sin\beta_{n+1}$$

The angles between b_{i+1} and b_i of the other finger links are (see fig.4)

$$\cos\gamma = \frac{a_i^{\,2} + b_{i+1}^{\,2} - \frac{L_i^{\,2}}{4}}{2a_i b_{i+1}}$$

Angle link a_i with axis x is

$$\beta_{a,i} = \beta_{b,i+1} - \gamma$$

Coordinates of points A_{i+1}, S_{i+1} are

$$x_{i+1} = b_{i+1}\cos\beta_{b,i+1}, \;\; y_{i+1} = b_{i+1}\sin\beta_{b,i+1}$$

$$x_{s,i} = a_i \cos\beta_{a,i}, \;\; y_{s,i} = a_i \sin\beta_{a,i}$$

Because S_i is at the center between A_{i+1} and A_i, the coordinates of A_i is

$$x_i = x_{i+1} + 2(x_{s,i} - x_{i+1}) = 2x_{s,i} - x_{i+1}, \; y_i = 2y_{s,i} - y_{i+1}$$

The distance of point A_i from coordinate origin is

$$b_i = \sqrt{x_i^{\,2} + y_i^{\,2}}$$

The angle of b_i with x-axis is (for $x_i = 0$ is $\beta_{b,i} = \pi/2$)

$$tg\beta_{bi} = \frac{y_i}{x_i}$$

Now let us turn the coordinate system (turn angle φ) to be the point A_1 on y axis, it means under bar center

$$\varphi = \frac{\pi}{2} + \alpha_{b1}$$

The angles β_{bi}, $\beta_{\alpha\iota}$ will be corrected

$$\beta_{bi} = \beta_{bi} - \varphi, \ \beta_{\alpha\iota} = \beta_{ai} - \varphi$$

The coordinate system will be now moved to be the point A_1 at coordinate origin. New coordinates of points A_i, B_i are

$$x_i = b_i \cos \beta_{bi}, \quad y_i = b_i \sin \beta_{bi} + b_1$$

$$X_i = R \cos \beta_{a,i\text{-}1}, \quad Y_i = R \sin \beta_{a,i\text{-}1} + b_1$$

If the value b_1 is the same for all fingers then the distance between wrist and bar centre is same.

The angles α_1, ..., α_4 can be calculated from

$$\alpha_i = \arctan \frac{y_i - y_{i-1}}{x_i - x_{i-1}}$$

Let us search points B_n and B_{n+1} with positive and negative x coordinate (if no point has negative x coordinate then the bar has too large diameter and cannot be griped). The bar vertical force F loads points B_{n+1}, B_n. The forces F_n, F_{n+1} at these points can be calculated from equilibrium conditions (see fig.6)

$$F_n \cos \alpha_{a,n\text{-}1} + F_{n+1} \cos \alpha_{an} = 0$$

$$F_n \sin \alpha_{a,n\text{-}1} + F_{n+1} \sin \alpha_{an} = F$$

5. Bone stress state and tendon forces

We calculated for all finger links (i=1,…,4) the coordinates of vectors $\vec{r}_i$ connecting points A_i and B_{i+1}, vector $\vec{c}_i$ connecting points A_i and A_{i+1} (see fig. 5)

$$r_{xi} = X_i - x_i, \ r_{zi} = Y_i - y_i$$

$$c_{xi} = x_{i+1} - x_i, \ c_{yi} = y_{i+1} - y_i$$

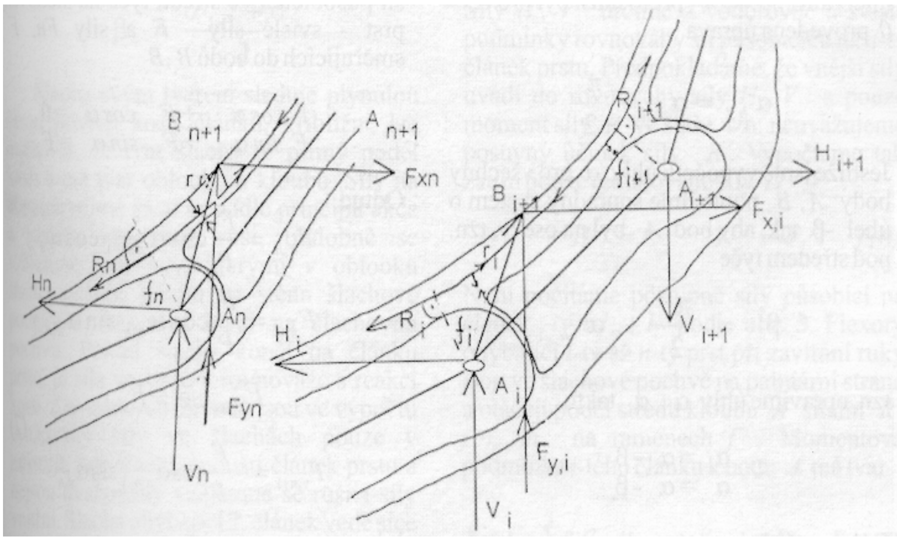
The tendon operates as a cable on pulleys near finger joints. The tendon force is considered at the nearest place from joint where the tendon intersects the angle axe β_i between the link axe directions.

$$\beta_i = \frac{\alpha_{i-1} + \alpha_i}{2}$$

The angle β_ι has direction cosines b_{xi}, b_{zi}.

Each finger link has its own flexor and extensor. The sum of the tendon forces at joint i is marked R_i. The perpendicular distance of force R_j from i-joint is f_i. The tendon's force R_i can be calculated from moment equilibrium condition. The force R_n is calculated from moment equilibrium for the last finger link to point A_n (see fig. 5).

$$R_n f_n + F_{zn} r_{xn} - F_{xn} r_{yn} = 0 \qquad (8)$$



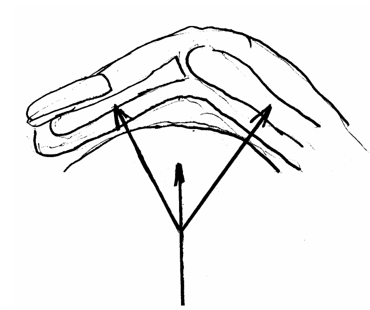


Fig. 6. Finger load

Fig.5. Tendon and external forces at last and i^{th} joint.

The horizontal and vertical joint forces H_n, V_n are calculated from equilibrium conditions at these directions

$$H_n = F_{xn} - R_n b_{xi},\ V_n = R_n b_{yi} - F_{yn} \tag{9}$$

Let us define H_{red}, V_{red} as joint forces without R_n effect

$$H_{red,n} = F_{xn},\quad V_{red,n} = -F_{zn} \tag{10}$$

The tendon and joint forces for the other finger links can be derived from the equilibrium conditions for the finger componets.

$$\begin{gathered} R_i f_i - H_{red,i+1} b_{y,i+1} - V_{red,i+1} b_{x,1} + F_{yi} r_{xi} - F_{xi} r_{yi} \\ H_{red,i} = H_{red,i+1} + F_{xi},\ \ V_{red,i} = V_{red,i+1} - F_{yi} \\ H_i = H_{red,i} - R_i b_{xi},\ V_i = V_{red,i} + R_i b_{yi} \end{gathered} \tag{11}$$

Each finger links has its own flexor with constant force at all length and R_i is sum of these forces near joint i. The moment of tendon forces R to joint increases from n^{th} to 2^{nd} joint and it is equal zero for 1^{st} joint. The tendon force must be positive (tensile) therefore the flexor of the 1^{st} finger link doesn't work but the extensor has a tensile force.

The bending moment M_i, normal and tangential forces N_i, Q_i at finger link centers (point S_i) are calculated from joint i (see fig. 1, 5). The positive bending moment has tensile part on the palmar side

$$M_i = \frac{1}{2}(V_i c_{xi} + H_i c_{yi}) - R_i f_i \tag{12}$$

$$N_i = H_i \cos\alpha - V_i \sin\alpha \tag{13}$$

$$Q_i = V_i \cos\alpha + H_i \sin\alpha \tag{14}$$

where R_i, H_i, V_i are calculated from (11) and

$$\cos\alpha = \frac{x_{i+1} - x_i}{L_i},\ \sin\alpha = \frac{y_{i+1} - y_i}{L_i}$$

Normal stresses at compact and spongy bone part are

$$\sigma_{x1} = \frac{N}{A_1 + \frac{E_2}{E_1} A_2} + \frac{M}{I_1 + \frac{E_2}{E_1} I_2} z, \qquad \sigma_{x2} = \frac{N}{A_2 + \frac{E_1}{E_2} A_1} + \frac{M}{I_2 + \frac{E_1}{E_2} I_1} z$$

where *N*, *M* were calculated from (12), (13), E_1, E_2 are modules of elasticity of compact and spongy bone part, A_1, A_2 and I_1, I_2 are areas and inertia modules there parts. The formulas suppose the centers of gravidity of compact and spongy part at the same place.

If the cross-section is considered approximately circle then the follow formulas can be used

$$\sigma_{x1} = \frac{N}{A_{r1}} + \frac{Mz}{I_{r1}}, \quad \sigma_{x2} = \frac{N}{A_{r2}} + \frac{Mz}{I_{r2}}$$

where r_1, r_2 are radiuses of compact and/or spongious parts of bones and

$$A_{r1} = \pi(r_1^2 - \lambda_1 r_2^2), \quad A_{r2} = \pi(\lambda_2 r_1^2 - \lambda_3 r_2^2)$$

$$I_{r1} = \frac{\pi}{4}(r_1^4 - \lambda_1 r_2^4), \quad I_{r2} = \frac{\pi}{4}(\lambda_2 r_1^4 - \lambda_3 r_2^4)$$

where

$$\lambda = \frac{E_2}{E_1}, \ \lambda_1 = 1 - \lambda, \ \lambda_2 = \frac{1}{\lambda}, \ \lambda_3 = \lambda_2 - 1$$

E_1, E_2 are moduli of elasticity for compact and spongious part of bone

The maximal tangential stress for around circle cross-section of bone is

$$\max \tau_1 = \max \tau_2 = \frac{0{,}90412966.Q}{2(r_1 - \frac{E_2}{E_1} r_2)} \left(\frac{r_1^3 - r_2^3}{I_{r1}} + \frac{r_2^3}{I_{r2}} \right)$$

where r_1, r_2 are external and internal bone radiuses.

The force *F* loading the hand will be now divided to forces F_i loading fingers. It is used the condition of the same value of maximal tendon force and/or the same maximal values of normal stress at all fingers (the algorithm is analogous). The cross-section areas of tendons are supposed at the same ratio as cross-section areas of bones at finger links centers. The follow algorithm is used. The fingers are the first loaded by force *F* and the maximal tendon forces or normal stresses are determined. Now the force *F* is divided to fingers according to dividing coefficients k_i. The dividing coefficients for the finger load are

$$k_i = \frac{1}{c \sigma_{\max,i}}$$

where

$$c = \sum_{i=1}^{n} \frac{1}{\sigma_{\max,i}}$$

and/or

$$k_i = \frac{1}{cR_{\max,i}}, \quad c = \sum_{i=1}^{n} \frac{1}{R\sigma_{\max,i}}$$

6. Conclusion

The presented algorithm was implemented on compute. The input values are anatomic dimensions of hand, diameter of griped object, grip force and grip type (tongs or bar). If the algorithm of tongs grip is used the number of operate finger links can be selected. The small tongs can be griped with a greater force if the tongs is put deeply to palm and the last finger links doesn't work. The program can be used for healthy hand and for hand with missing finger links or with some finger which doesn't work.

The results of program can be used for design of finger joint implants. The calculated bending moments and normal and tangential joint forces can be used as load for implant searched by the finite element method.

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