DE GRUYTER OPEN

Int. J. of Applied Mechanics and Engineering, 2014, vol.19, No.3, pp.633-642
DOI: 10.2478/ijame-2014-0044

THE ANALYSIS OF PEDALING TECHNIQUES WITH PLATFORM PEDALS

A.A. STĘPNIEWSKI* and J. GRUDZIŃSKI
Faculty of Production Engineering
University of Life Sciences in Lublin
Akademicka 13, 20-950 Lublin, POLAND
E-mails: andrzej.stepniewski@up.lublin.pl
jerzy.grudzinski@up.lublin.pl

The paper analyzes a pedaling technique with platform pedals in which the influence of the geometric and tribological parameters on the torque course of the active forces in the crank rotation axis is determined. Distribution of forces of feet acting on pedals as a function of the crank rotation angle was performed and on this basis the specific pedaling zones and their ranges and the courses of the value of variable active torque and pedaling work during the full cycle were determined. The course of changes in the movements in the ankle joint is described with a function depending on the crank and limb position and loading of the joint. A numerical example has also been presented and a discussion of the results has been carried out.

Key words: cycling, platform-pedal, pedaling, cycling efficiency.

1. Introduction

The efficiency of conversion of muscle energy into kinetic energy of a bicycle is a derivative of the following: 1) design parameters - resistance of movement of the driving system, rolling resistance of tires, gear ratios; mass - mass of the bike and cyclist; 2) geometry parameters - bicycle dimensions, cyclist's body size and position (Defraeye *et al*., 2010); 3) environmental parameters - the landform, drag. In addition to optimizing the design and geometrical parameters, the pedaling technique can also be improved (Sickle and Hull, 2007).

This paper discusses a popular issue about the pedaling technique with platform pedals. The first problem that arises while describing the geometry of the limb movement is the inability to determine the course of changes of the angle in the ankle joint using the geometrical dependencies. The course of changes of the angle in the ankle joint can only be roughly determined on the basis of a number of publications, including the results of experimental studies in which the courses of angular changes (Cockcroft, 2011; Park *et al*., 2012; Li Li and Caldwell, 1998) were described. In subsequent cycles, and in similar positions, there are differences between the courses resulting from muscle fatigue and adaptation to the current cycling speed (Neptune and Herzog, 2000). Differences for the left and right leg are 17 degrees.

The proposed correlation allows the formation of courses of position changes in the ankle joint in the ranges determined by experiments. This consists of a sinusoid with variable amplitudes, period and phase, the rectilinear course determining the inclination of the total course to the horizontal axis and a component taking into account the change in displacement as a result of the acting load.

The effect of displacement of ankle joint on the geometry of the pedal load and the effect of the coefficient of friction between the pedal platform and shoes on the ranges of individual pedaling zones

* To whom correspondence should be addressed

and work expended by the cyclist have been investigated. The aim of the simulations was to analyze the driving capabilities of a bicycle with platform pedals and to specify recommendations on the pedaling technique.

2. Geometry of movement

The lower limb with the crank creates a closed kinetic chain – an articulated pentagon with three drives, or in a different approach - an open kinematic chain with three driven elements, in which the end of the last element moves in a circle. If the relative movement between the pedal platform and the adjacent surface of the sole is assumed, then an articulated hexagon is created with five rotating pairs and one progressive pair. Assuming that the kinematic chain moves in one plane, all the kinematic pairs, including the progressive pair, will be pairs of the fifth grade.

A pedaling cycle of one limb begins with actuation of the foot on the pedal, located at the upper position ($\alpha_k = 0$) and ends when reaching a position in which the application of the force component perpendicular to the crank is not possible. During return to the upper position, the limb does not exert force on the pedal platform and the other limb takes over the job. Figure 1a illustrates the so-called “main zones of application of forces while pedaling” in the pedaling cycle: I - top, II - front, III - down, IV - back. Zones 1-4 are called segmental zones. Also the movements of the joints in the individual zones are determined: 1, I, 2, II - straightening of the hip joint and the ankle, 3, III, 4 - straightening of foot and in the hip joint, bending the ankle, IV - bending at the hip joint and the ankle (Poliszczuk, 1996; Höchtl *et al*., 2010).

a)

b)

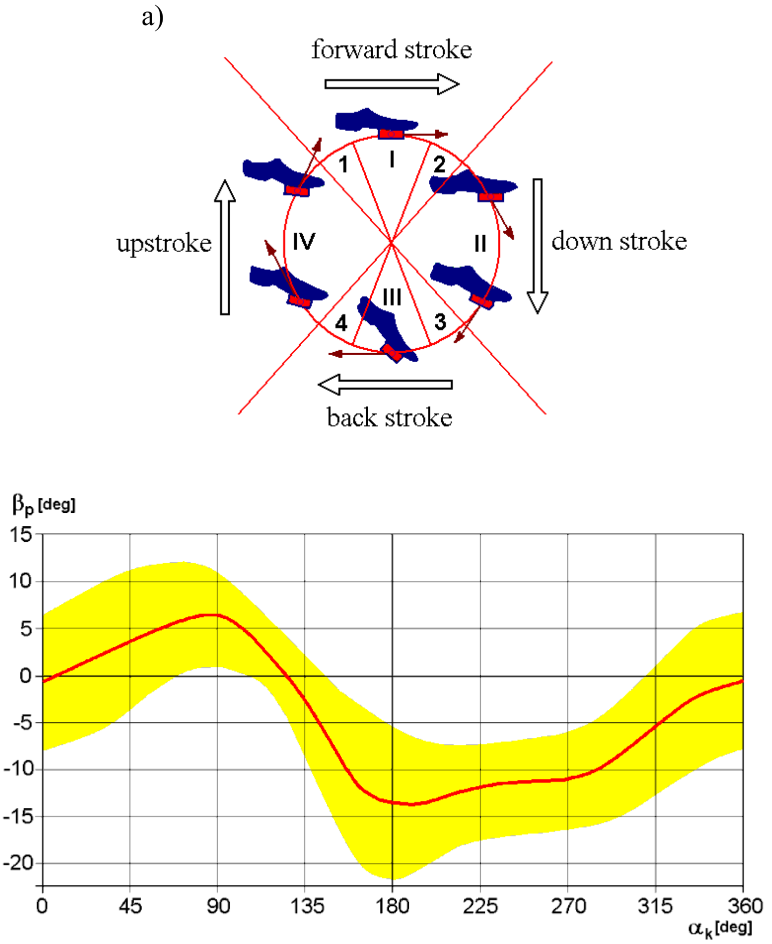


Fig.1. Pedaling geometry; a – a diagram of major forces application zones while pedaling, b – the angular displacement in the ankle joint.

Experimentally determined angular courses in ankles β_p (α_k), can be summed up in the average "tolerance zone" for both legs marked in Fig.1b.

In order to determine the course $\beta_p(\alpha_k)$, a manner that respects the natural physiology of movement may be proposed. When the force generated by the muscle is greater than the load, as it happens during cycling, then the type of muscle work is concentric. The muscle overcoming the external forces is shortened, i.e., it acts opposite than loaded vulnerable system, which moves in accordance with the direction of the loading force. In addition, the "elasticity" ratio of the joint increases with increasing the maximum load due to increased calf muscle activation.

Considering the possibility of designing the course depending on the individual characteristics, taking into account the physiology of the muscles, the following correlation can be suggested

$$\beta_p = A_\beta \sin\left(T_\beta \alpha_k + \phi_\beta\right) - a_\beta\left(\alpha_k - B_x\right) + B_y + \beta_0 + \frac{M_{R3}}{k_s}, \tag{2.1}$$

while

$$M_{R3} = F_{3,3,y} l_3, \tag{2.2}$$

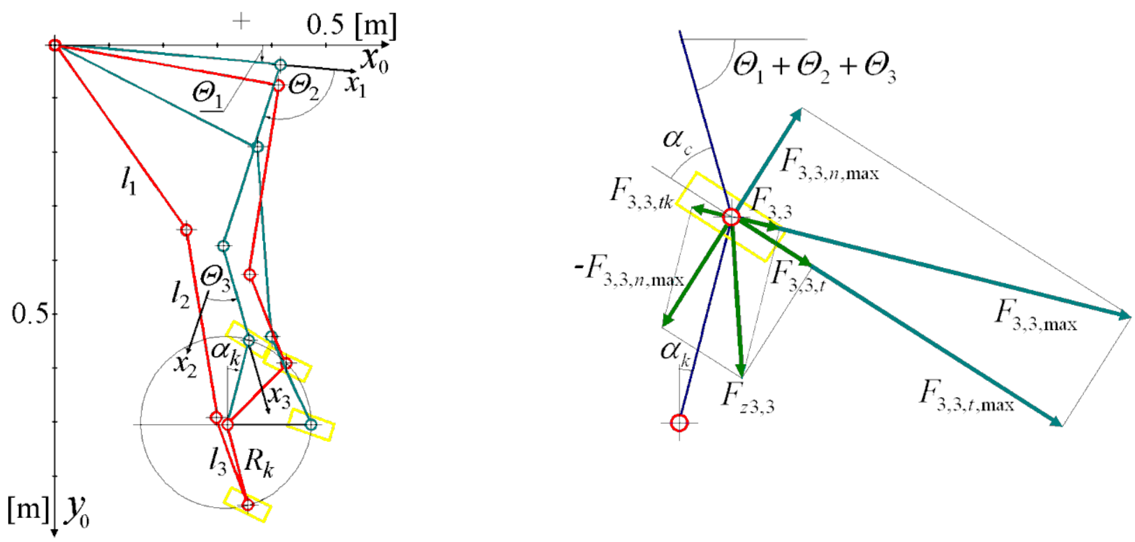
and assuming a linear dependency of the "elasticity" ratio of the joint on the maximum down stroke force

$$k_s = k_p \left|F_{3,3,\max}\right|. \tag{2.3}$$

3. Active forces

The active force torque acting in the crank rotation axis during cycling is not constant, because pedaling consisting in acting with a constant force perpendicular to the crank is not possible due to the distribution of forces. Figure 2 shows a distributions of the force vector perpendicular to the crank $F_{3,3,\max}$ (initially a constant value was established) for the normal $F_{3,3,n,\max}$ and the tangent $F_{3,3,t,\max}$ directions to the pedal platform for four angular positions. It was assumed that the value of the vector friction force (sketch) $F_{3,3,t} = 0.8F_{3,3,n,\max}$. The actual value of the active force of the vector $F_{3,3}$ is set by projection of the sum of vectors $F_{3,3,t}$ and $F_{3,3,n,\max}$ ($F_{z3,3}$) to the direction perpendicular to the crank.

a



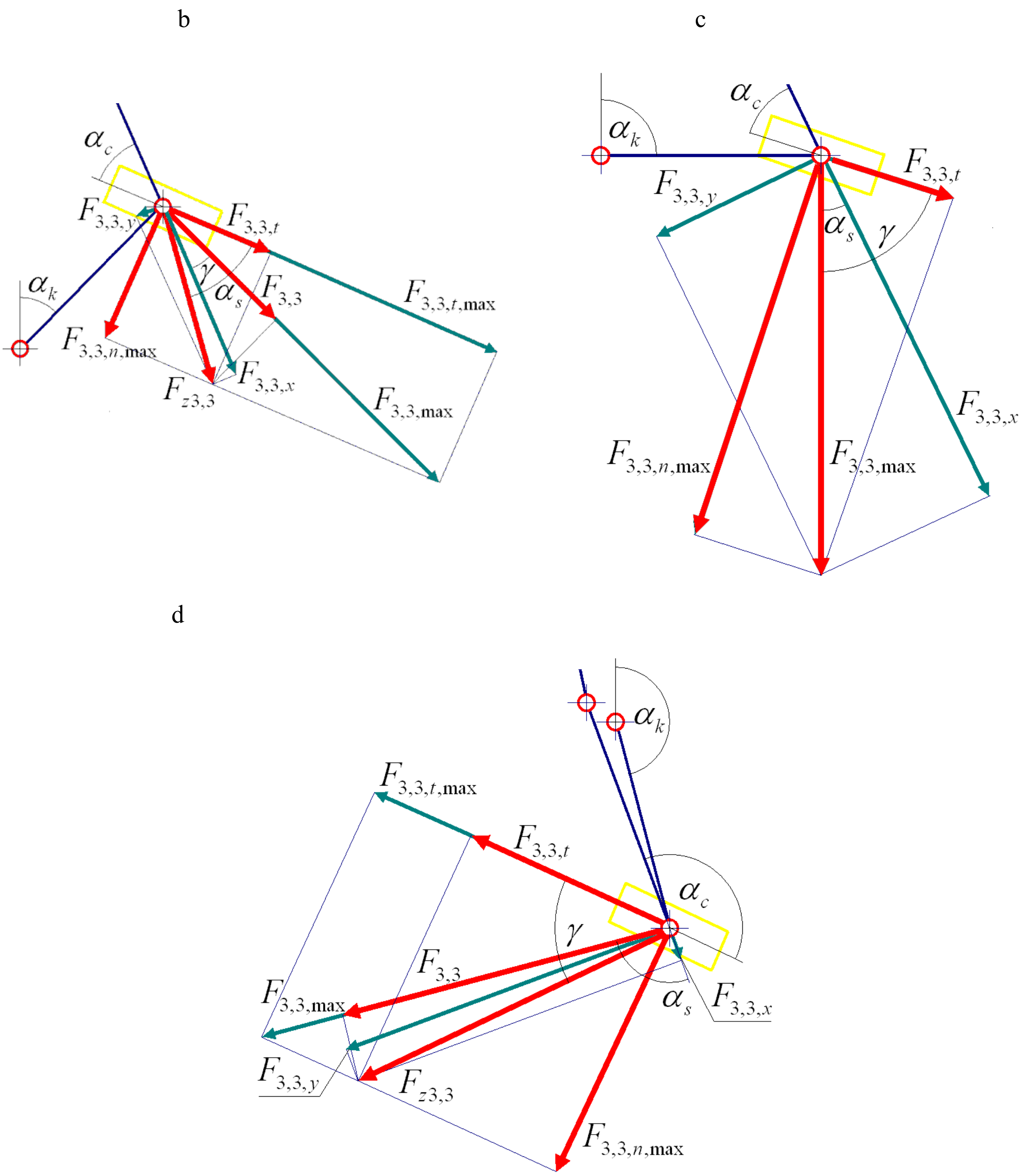


Fig.2. The pedaling zones; distributions of forces in individual pedaling zones; a - for $\alpha_k = 15°$, b - for $\alpha_k = 45°$, c - for $\alpha_k = 90°$, d - for $\alpha_k = 165°$.

The component values of tangential $F_{3,3,t,\max}$ and normal $F_{3,3,n,\max}$ of the set of active force $F_{3,3,\max}$ to the contact plane of the pedal platform with the sole, are determined by the dependencies

$$F_{3,3,n,\max} = F_{3,3,\max} \sin(\alpha_s + \alpha_c), \tag{3.1}$$

$$F_{3,3,t,\max} = F_{3,3,\max} \cos\left(\alpha_s + \alpha_c\right), \tag{3.2}$$

while

$$\alpha_s = \Theta_1 + \Theta_2 + \Theta_3 + \alpha_k . \tag{3.3}$$

When pedaling from the upper position of the pedal to a bottom position in which applying pressure is still possible, four zones can be distinguished.

In the first zone in which the direction of the component of the normal active force is directed from the plane of the pedal – Fig.2a, in order to obtain the assumed tangential to the crank force, one should act with a force perpendicular to the pedal in the opposite direction to its plane and with the tangential force of a value exceeding the frictional force. In the case of a platform pedal with no additional tethering (latch) it is not feasible. Activation with only normal force to the plane of pedal - $F_{3,3,n,\max}$ directed opposite to the force $F_{3,3,n,\max}$, will rotate the crank in the opposite direction. However, considering the possibility of actuation on the pedal with additional tangential force $F_{3,3,t}$, the balancing of the frictional force can cause rotation of the pedal in the right direction. Due to the difficulty of such action which requires maintaining an appropriate balance between the normal and tangential forces it was assumed that

$$F_{3,3,n} = 0 , \qquad \text{so} \qquad F_{3,3,t} = 0 \qquad \text{and} \qquad F_{3,3} = 0 . \tag{3.4}$$

In the second zone, the component of the normal active force is directed to the plane of the pedal and the tangential component exceeds the value of the appearing friction between the sole and the pedal – Fig.2b, i.e.

$$\left|F_{3,3,t,\max}\right| > \mu_{bp} F_{3,3,n,\max} . \tag{3.5}$$

In this case, the maximum value of the tangential force cannot exceed the frictional force, so

$$F_{3,3,t} = \mu_{bp} F_{3,3,n,\max} \operatorname{sgn}\left(F_{3,3,t,\max}\right). \tag{3.6}$$

To make pedaling possible, it is necessary to change the value and direction of the active force. The new value of this force is determined by the dependency

$$F_{z3,3} = F_{3,3,n,\max} \sqrt{\mu_{bp}^{\,2} + 1} , \tag{3.7}$$

so the vector of the component perpendicular to the crank will decrease in value and will be

$$F_{3,3} = F_{z3,3} \cos\left(\gamma + \alpha_c - \alpha_s\right), \tag{3.8}$$

where

$$\gamma = \operatorname{atan} \frac{F_{3,3,n,\max}}{F_{3,3,t}} \quad . \tag{3.9}$$

Coordinate values of the vector active force acting on the crank, as defined in the system of coordinates $\{x_3, y_3\}$ with the origin at O_3, are determined by the following relationships

$$F_{3,3,x} = F_{z3,3}\cos(\gamma + \alpha_c), \tag{3.10}$$

$$F_{3,3,y} = F_{z3,3}\sin(\gamma + \alpha_c). \tag{3.11}$$

In the third zone, the component of the vector active force is directed to the pedal plane and the value of the tangential component is smaller than the frictional force appearing between the sole and the pedal – Fig.2c, i.e.

$$\left|F_{3,3,t,\max}\right| < \mu_{bp} F_{3,3,n,\max}\,. \tag{3.12}$$

In this case, a non-slip frictional contact between the sole and the pedal is provided and the slip is not possible. Vector coordinate values of the active force acting on the crank, as defined in the system of coordinates with the origin at O_3, are determined by the relationships ($F_{z3,3} = F_{3,3,\max}$)

$$F_{3,3,x} = F_{3,3,\max}\cos(\gamma + \alpha_c), \tag{3.13}$$

$$F_{3,3,y} = F_{3,3,\max}\sin(\gamma + \alpha_c). \tag{3.14}$$

In the fourth zone the component of the vector active force is directed to the plane of the pedal and the tangential component exceeds the value of the frictional force appearing between the sole and the pedal, and its direction is opposite to the direction appearing in the second zone – Fig.2d. The calculations of the active force $F_{3,3}$ are according to the relationship in the second zone.

In the fifth zone - applying pressure to the pedal is not possible, the pedal is in the negative phase of rotation. During pedaling any increase of the active force $F_{3,3,\max}$ is possible in the third zone - as well as of force $F_{z3,3}$, in the second and fourth zone - (less favorable way) by stronger activation on the pedal. The increase of the force $F_{3,3,\max}$, increases values of forces $F_{3,3,t}$ and $F_{3,3,n}$ but does not change the values of their quotient. With dynamic, "uneven" pedaling, the extreme value of the active force should be applied to the crank when the tangential component of the force $F_{3,3,t}$ changes the direction (then $\alpha_s + \alpha_c = 0{,}5\pi$).

The value of the torque of the active force depends on the angle of position of the crank

$$M_{k,c}(\alpha_k) = F_{3,3}R_k\,. \tag{3.15}$$

The determined this way active torque value does not depend on pedaling speed, which is not entirely true. During stress pedaling, the forces acting on the muscle may exceed the forces generated by this muscle, which is referred to as eccentric work. The effect of eccentric strength training is to increase the force depending on the speed and frequency of load changes.

The work done by the cyclist $W_r(\alpha_k)$ in the cycle can be determined by the relationship

$$W_r(\alpha_k) = \int_{\alpha_{kp}}^{\alpha_{kk}} M_{k,c}(\alpha_k)\,d\alpha_k\,. \tag{3.16}$$

4. Numerical example

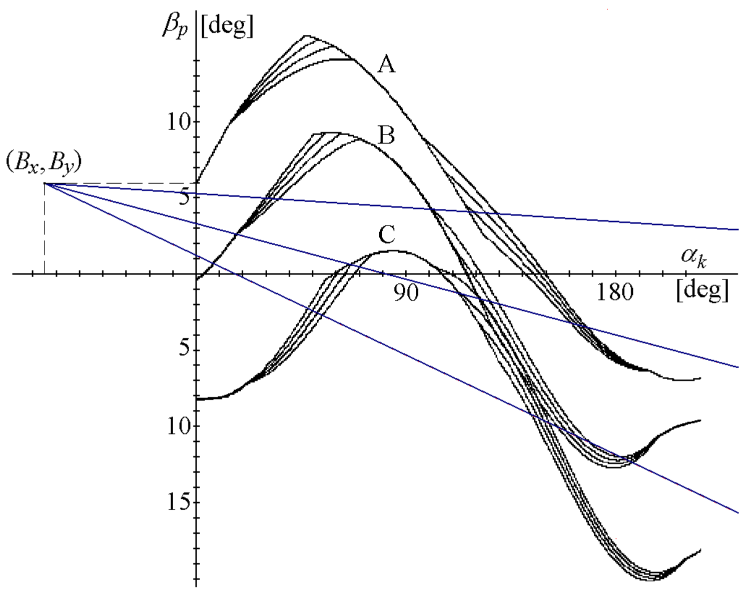
For the calculation, the following data were assumed: limb segments length: $l_1 = 0.42\ m$, $l_2 = 0.35\ m$, $l_3 = 0.19\ m$, the length of the crank $R_k = 0.175\ m$, coordinates of the axis of pedal rotation in the system $\{x_0, y_0\}$: $(x_{04}, y_{04}) = (0.32\ m, -0.68\ m)$, the maximum value of the active force $F_{3,3,\max} = 120\ N$, the values of angles: $\alpha_c = 50°$. In order to determine the quantitative effect of the friction coefficient between the pedal surface and the sole, the calculations were made for four values of the coefficient μ_{bp} - *0.3*, *0.5*, *0.7*, *0.9*. The extreme values of the coefficients were taken from tables in such a way that they characterized pedaling in footwear not providing good frictional contact (wet leather-synthetic material) and footwear that provides a high friction force (soft rubber - synthetic material). The calculation results are shown in Fig.3 and Tab.1.

Figure 3a shows the displacement courses in the ankle joint for three selected sets of values of the constants of Eq.(2.1) - courses A, B and C, in such a way that the waveforms A and C would define the limits of the experimental “tolerance zone” and the waveform B would be contained in the center of the zone. For each course displacement, the torque and the pedaling zone ranges were determined which are shown in Figure 3b and the values of the work done during the cycle are presented in Tab.1.

Table 1. The values of the work done during the cycle.

μ_{bp}		*0.3*	*0.5*	*0.7*	*0.9*
W_r [J]	A	*70.80*	*78.28*	*84.84*	*90.44*
	B	*74.47*	*82.58*	*89.44*	*95.32*
	C	*74.42*	*82.62*	*89.88*	*96.18*

a



b

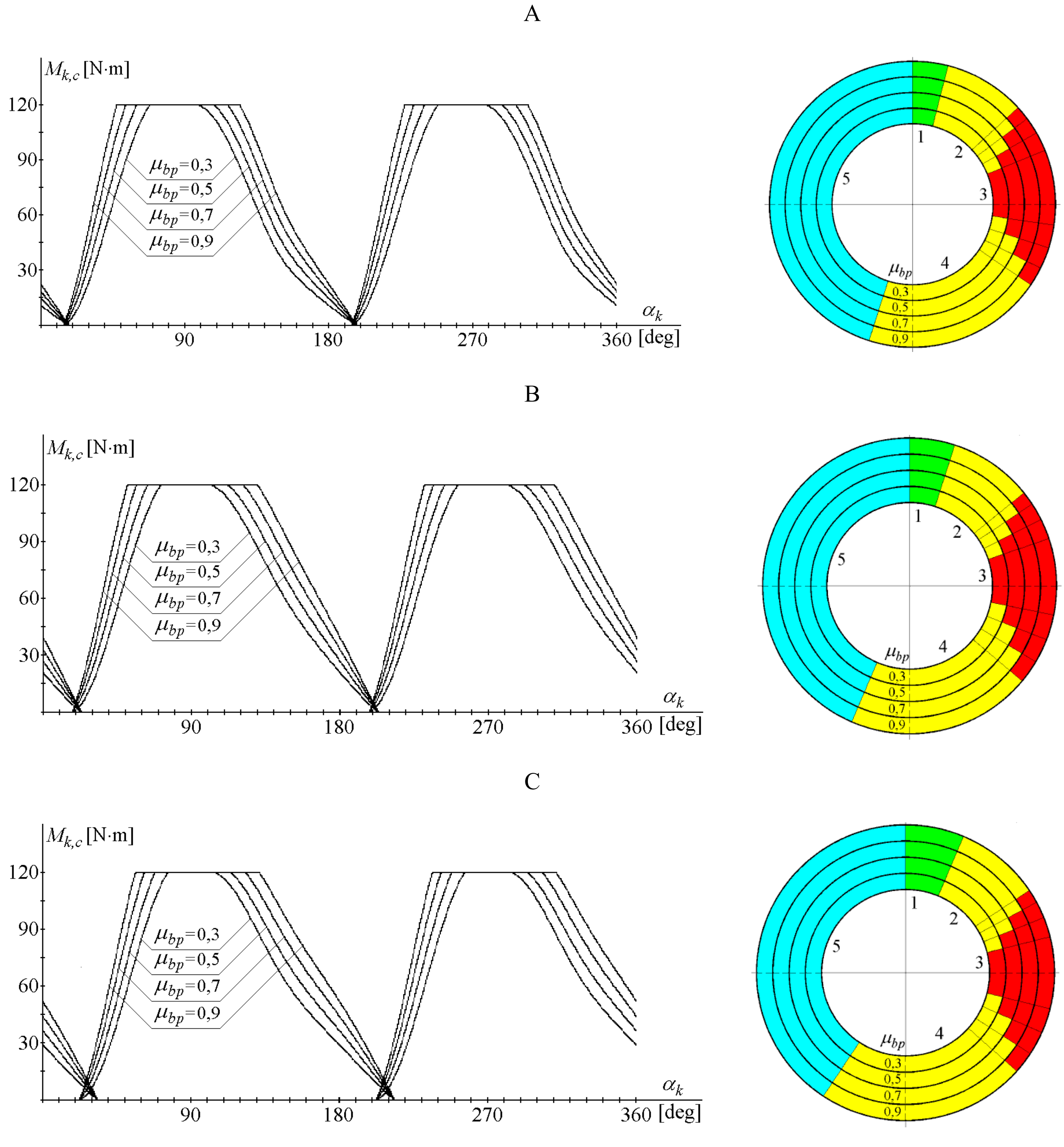


Fig.3. The calculation results, a - displacements in the ankle joint while exerting pressure on the pedal; A, C- extreme waveforms, B - middle waveform, b - torque and ranges of pedaling zones for three courses of angles in the ankle joint and selected values of the coefficients of static friction of the platform and shoes.

5. Discussion and conclusions

The measure of cycling efficiency is the value of work done on the set angular way of the pedal crank. On the basis of the example made in order to obtain a more efficient movement, the course of displacement in the ankle joint should be in the range of $\alpha_k = 0$ according with course A, and then after the entry into zone 3 ($\alpha_k = 90°\pm30°$) progressively "move" in the course C. This involves, however, the need for major displacements in the ankle joint (about $35°$) and the greater work intensity of the calf muscle, which may be possible only during a short-term effort.

With a good traction of shoe to pedal and the normal cycling which does not require performing large ranges of changes in the ankle joint displacements (up to $22°$) the efficiency of pedaling reaches *70%* $W_{r,\max} = 2\pi R_k F_{3,3,\max} = 132\ J$.

The increase in the traction of platform pedals to shoes has a positive effect on pedaling efficiency, which is obvious. The range of the third zone gets increased at the expense of the second and fourth zones. The value of the work done increases. A lower value of the friction coefficient reduces the range of the third zone and increases the range of the second and fourth zones where it is necessary to reduce the value and the direction of the active force $F_{3,3}$.

Summing up, in order to improve the cycling technique, comfortable athletic shoes with soles providing the best combination of friction with the pedal and not restraining movement at the ankle joint, should be used. It is very important to train the movement in the ankle joint in the range of displacements from $5°$ (crank up position) to - $15°$ (crank down position) to allow an increase of the zone of exerting force.

Nomenclature

A_β – course amplitude [rad]
a_β – directional coefficient of straight line defining inclination of the course to the horizontal axis
(B_x, B_y) – coordinate, common point of straight lines determining inclination of waveforms to the horizontal axis [rad] (see the numerical example – Fig.3a)
$F_{3,3,max}$ – the maximum value of the active force [N]
$F_{3,3,y}$ – force perpendicular to the direction joining the centers of rotating pairs of the ankle and the pedal platform [N]
k_p – value of the muscle shortening coefficient [$m\cdot$rad^{-1}]
k_s – coefficient of "elasticity" (excitation, recovery) of ankle joint [$N\cdot m\cdot$rad^{-1}]
l_3 – distance between axes of rotating pairs centers of the ankle joint and the pedal [m]
M_{R3} – the value of the torque loading the ankle joint [$N\cdot m$]
T_β – the period of the course [rad]
α_c – constant angle contained between the surface of the pedal platform and a line joining the centers of rotary pairs of ankle and pedal [rad]
α_k – angle of crank rotation measured from the top position [rad]
α_{kp}, α_{kk} – initial and final position of the crank [rad]
β_0 – angle in the ankle joint at no load [rad]
φ_β – phase of the course [rad]
μ_{bp} – coefficient of static friction between the pedal platform and the sole
Θ_i – angle position in the hip, knee and ankle joints, respectively [rad]

References

Cockcroft S.J. (2011): *An evaluation of inertial motion capture technology for use in the analysis and optimization of road cycling kinematics.* – Stellenbosch University.

Defraeye T., Blocken B., Koninckx E., Hespel P. and Carmeliet J. (2010): *Aerodynamics study of different cyclic positions: CFD Analysis and full scale wind tunnel tests.* – J. Biomechanics, vol.43, pp.1262-1268.

Höchtl F., Böhm H. and Senner V. (2010): *Prediction of energy efficient pedal forces in cycling using musculoskeletal simulation models.* – Proc. Engineering, vol.2, pp.3211-3215.

Li Li and Caldwell G.E. (1998): *Muscle coordination in cycling: effect of surface incline and posture.* – J Appl. Physiol., vol.85, pp.927-934.

Neptune R.R. and Herzog W. (2000): *Adaptation of muscle coordination to altered task mechanics during steady-state cycling.* – J. of Biomechanics, vol.33, pp.165-172.

Park S.-Y., Lee S.-Y., Kang H.C. and Kim S.-M. (2012): *EMG analysis of lower limb muscle activation pattern during pedaling experiments and computer simulations.* – Int. J. of Precision Engineering and Manufacturing, vol.13, No.4, pp.601-608.

Poliszczuk D.A. (1996): *Cycling. Theory and practice of training*. – Wyd. COS. Warsaw.

Sickle Van Jr J.R. and Hull M.L. (2007): *Is economy of competitive cyclic affected by the anterior-posterior foot position on the pedal.* – J. Biomechanics, vol.40, pp.1262-1267.

Received: May 15, 2014
Revised: May 17, 2014