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EVALUATION OF FOUR-BAR MECHANISMS FOR BICYCLE PEDALS

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As the Global Warming destroys gradually the life on the earth, vehicles driven by clean energy are of importance. Therefore, in this paper, mechanisms for bicycle drivetrain are scrutinized starting from its initial invention to attract attentions of the people in the field of mechanism. Some recent health problems caused by design of modern bicycles are highlighted. Optional several mechanisms such as crank rocker, double crank, double rocker, slider crank, and inverted slider crank for the drivetrain of bicycle are evaluated. Each of them was assessed in the perspective of applicability by using shelf-ready products. A double-rocker mechanism is schematically designed by using GeoGebra. An analysis for the geometric constraints of the design and torque are presented. Finally, the double rocker was concluded to design a pedal drivetrain. An optimization was carried out by using Microsoft Excel. The optimal dimensions were delivered. The maximum torque 90 Nm. The maximum energy can be produced is 600W.

Keywords: *Four-bar linkage mechanism, innovative pedal design, double-rocker mechanism, bicycle drivetrain, pedaling.*

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ТӨРТ ТАЯҚША МЕХАНИЗМІ ВЕЛОСИПЕД ПЕДАЛІ ҮШІН БАҒАЛАУ

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Глобалдық жылыну Жердегі өмірді біртіндеп жойып жатқанда, таза энергиямен жүретін көліктердің маңызы зор. Сондықтан осы мақалада велосипед жетегінің механизмдері оның бастапқы өнертабысынан бастап механика саласындағы адамдардың назарын аудару үшін мұқият зерттелген. Заманауи велосипедтердің дизайнына байланысты кейбір соңғы денсаулық проблемалары атап өтілген. Велосипед жетегіне арналған кривошипті-тербелме, қос кривошип, қос тербелме, кривошипті-сырғымалы және инверттелген кривошипті-сырғымалы сияқты бірнеше механизмдер бағаланды. Олардың әрқайсысы дайын өнімдерді пайдалану тұрғысынан қолдануға болатыны бағаланды. Қос тербелме механизмі GeoGebra бағдарламасын пайдалана отырып, схемалық түрде жасалған. Дизайнның геометриялық шектеулері мен моментіне тал-

дау ұсынылған. Соңында қос тербелме педаль жетегін жобалау үшін таңдалды. Microsoft Excel бағдарламасын пайдалана отырып оңтайландыру жүргізілді. Оңтайлы өлшемдер анықталды. Ең үлкен айналу моменті 90 Нм. Өндірілетін ең көп энергия 600 Вт.

Түйін сөздер: *велосипед педаль механизмі, төрт таяқша механизмі, инновациялық педаль дизайны, қос маятник механизмі, велосипед жетек жүйесі, педаль айналдыру.*

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ОЦЕНКА МЕХАНИЗМА ЧЕТЫРЕХ СТЕРЖНЕЙ ДЛЯ ПЕДАЛИ ВЕЛОСИПЕДА

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По мере того, как глобальное потепление постепенно разрушает жизнь на Земле, транспортные средства, работающие на чистой энергии, приобретают особое значение. Поэтому в данной статье механизмы привода велосипеда тщательно исследуются, начиная с его первоначального изобретения, чтобы привлечь внимание людей в области механики. Выделены некоторые современные проблемы со здоровьем, вызванные конструкцией современных велосипедов. Оценены различные механизмы, такие как кривошипно-шатунный, двойной кривошип, двойной шатун, кривошипно-ползунный и инвертированный кривошипно-ползунный для привода велосипеда. Каждый из них был оценен с точки зрения применимости с использованием готовых к использованию продуктов. Механизм двойного шатуна был схематически спроектирован с использованием GeoGebra. Представлен анализ геометрических ограничений конструкции и крутящего момента. Наконец, механизм двойного шатуна был выбран для проектирования педального привода. Оптимизация была проведена с использованием Microsoft Excel. Были определены оптимальные размеры. Максимальный крутящий момент составляет 90 Нм. Максимальная производимая энергия составляет 600 Вт.

Ключевые слова: *механизм педали велосипеда, механизмы четырех стержней, инновационный дизайн педали, механизм двойного маятника, система привода велосипеда, кручение педали.*

Introduction. The quality of succulent feed for animal husbandry is determined by the availability of full the first invented vehicles in the history for transportation was the wheelbarrow and the chariot which were used to carry foods or soldiers during ancient Egypt [1]. The chariot was used to be driven by horses. However, the wheelbarrow was driven by manpower. Therefore, the first manpowered vehicle was the wheelbarrow. But the first manpowered and man-carrying vehicle is the hand-cranked wheelchairs for dis-abled people in seventeenth century [2]. Afterwards, in Japan, a scholar namely Kuheiji-Tokimitu Hisaishi had written about a boat-like vehicle with three wheels in 1730 [3]. Amidst the Napoleonic Wars in 1812, both Europe and New England faced a series of poor harvests, with Germany particularly affected by grain shortages due to wartime plundering. Karl von Drais sought approval from the Grand Duke of Baden to patent a four-wheeled humanpowered wagon[4]. Subsequently, the eruption of Mount Tambora in 1815 caused a shortage of food in Europe [5]. Several horses died. Thus, the aids from other countries could not be carried to the locations where people were in need. Karl Drais in Germany invented the first man-powered four-wheel vehicle to transport foods or people. However, the pedal design was not good enough.

After a few years, Drais produced Laufmaschine which had only two wheels contrary to the Fahrmaschine to create an ability to go through narrow ways like paths in the forest [6]. The ice skating was the main inspiration for the innovation of the Fahrmaschine[7]. Because of balance problem in two wheeled Laufmaschine, a pe-dal mechanism was not included in the new design. However, the steering mechanism made use of the caster affect which is still used in present modern designs. Drais created a range of designs with two, three, four wheels in progressing years. Although Drais's patent applications to various countries in Europe were declined, the idea of two-wheeled man-powered machine soon spread to the whole western world [8]. Moreover, new vehicles were invented such as roller-skate [9].After spread to Europe, the Laufmaschine was called as velocipede. Furthermore, the velocipedes were im-proved by adding a drive mechanism.

The drive mechanism of velocipedes consisted of hand-driven, foot-driven or both[10]. Before the mechanism driven velocipede, there were a crank-driven front-axel velocipedes [11]. This type of designs is still in use for bikes in kindergartens. However, the design is difficult to balance when it is two-wheeled. Moreover, having cranked-front-axel fixes the rotation ratio as one. Therefore, achieving an efficient design requires front wheel with a very big diameter. Treadle-driven two-wheeler was introduced by Kirkpatric Macmillan in 1839[13]. This design was the first bicycle with a pedal mechanism made of four-bar mechanism namely crank-rocker. However, it was failed about the motion of bicycle to downhill. Because the crank assembled to the rear wheel turned into a driving element of the mechanism during the motion to downhill. Subsequently, a wired tension wheel and tangential lever bar were invented by Eugene Meyer[4]. They were not feasible in application in terms of speed. So soon enough they were faded away. Pierre and Ernest Michaux introduced a front-axel cranked bicycle namely high-wheeler French velocipede in 1863[13]. This was almost the same design with Lallement's design in 1866. They suffered from motion trans-mission ratio. The gear system was introduced in Britain in 1870[12]. This system was so heavy that prevented to speed up.

As the time pass, people contributed various improvements to the bicycle technology. James Starley and William Hillman had introduced the Ariel machine : an elegant all metal high-wheeler with wire-spoke wheels[14]. The genuine part of their design was not only the drive mechanism but also the wire-spoke wheels with large diameters without high inertia. Queen Victoria was so attracted to their design that she ordered two of them. The design was later regarded as a female bicycle and named as Starly's Royal Salvo Tricycle in 1873. Starley incorporated with Smith Machine Company in Jersey to renovate a high-wheeler design which was safer and two-wheel in 1881[14]. Although the design was better than old versions, it could not attract the trend. By the end of 1889, Starley proposed the idea of differential gear[13]. Dursley Pedersen created the design of the bicycle commonly used nowadays in 1890 [15]. This was the last innovation on the mechanism design of the bicycle driving system. After the chain mechanism was contributed, the drive mechanism was not innovated.

It is very interesting that although the invention of the wheel was 4th millennium BC, as humankind started to use it for transportation of himself independently in 18th century AC. That shows despite many inventions on bicycle pedal mechanism, there may be opportunities for new inventions. All bicycle designs in the literature include seat or saddle. The saddle was used to relax the muscles in the legs. Therefore, it helped to save energy as much as five times of the energy consumed during walking per kilometer[13]. However, the friction and the pressure between legs and the saddle were realized to be causing disorders[16]. Moreover, settings of saddle have significant place in riding bicycle. Otherwise, there may be disorders in the knees[17]. The damage in the knee is caused by the force applied by the muscles in the leg. However, the same disorder would not occur, if it were the climbing upstairs [18,20]. Because, when it is the climbing upstairs, the motion is counterpart of the propulsion phase of pedaling and it has the lowest force applied on knee joints [20]. However, when it is the pedaling, the load is dependent to the gear system which can increase and decrease the radius of torque. Addition to that is the angle of the knee is dangerously adjusted in public, when the pedal is in the position of propulsion[19].

In this paper, an analysis of four-bar mechanisms for pedal mechanisms of bicycle is presented . The reasons of design revision of traditional bicycle are explained in detail. The geometric constraints are determined. The chain drive systems are regard-ed as vulnerable in traditional bicycles. This vulnerability may cause high friction and energy lose[21]. Moreover, the motion during climbing upstairs was taken as reference to pedaling mechanism. Therefore, beside the force produced by muscles, the body weight will be applied to the chain drive system which can easily be deformed under the high torque compared to traditional bicycles[22]. The torque is calculated, and analysis are presented. Finally, a conclusion is given for this study.

Research methodology and results. One of the most efficient exercise motions for muscles on Lumbar erector spinae is the stair-climbing [27]. However, the best effect of stair-climbing on an adult can be obtained, if double stairs are climbed at once [28]. This exercise is named as stair lunge. A standard stair has a height of 20 cm. Therefore, two stairs can cause a right angle between the tibia and the femur in a young average person. This position is a limit of safe motion of knee joint for a healthy user. Therefore, the same limitation will be valid for the mechanism of bicycle pedal. The motion of the pedal mechanism will be like the motion of the stair-climbing. Thus, the pedal will trace a circular arc as a trajectory. This is an accepted trajectory for comfortable motion of foot climbing stairs [29]. After one stroke of the pedal, the leg must be vertical. Consequently, the range of the motion for the pedal mechanism can be derived from the trajectory limitations of the leg climbing stairs as shown in Figure 1. The most important criteria of the motion of climbing stairs are angles during the transition between steps; θ1, θ2, θ3 which must be higher than a right angle to protect health of the knee. The overall height of the double step in standard is 40 cm. However, this height can be different for every individual. Thus, the user will adjust his/her step height accordingly.

Figure 1 **–** The motion of climbing stairs(stair lunges)

Four-bar linkage mechanisms are rigid systems that have input and output of the motion. The motion could be transformed from rotational to translational or wise versa. The linkages can also provide a motion consisted of rotation and translation. Therefore, they were considered for the pedal mechanism in this paper. There are several options in the inversion of four-bar mechanisms such as crank-rocker, double crank, double rocker, slider-crank, and inverted slider-crank. The inverted slider-crank mechanism has joints with flat surfaces. Therefore, the design may wear out earlier than the joints with cylindrical contact surface or produced expensively due to protective coating processes [25]. Thus, the mechanisms with sliders were omitted. The double-crank mechanism provides a complete rotation for both cranks in the linkage. The cranks will require high wheeled design to prevent pedal crashing to the ground. Therefore, it is hard to design a pedal mechanism from this type of system. A pedal mechanism is expected to rotate the rear wheel one complete rotation to sustain the translation of the chassis. This is the most efficient way of driving the system. How-ever, if one complete rotation could not be provided, then there must be a ratchet as used in the rear hub of traditional designs.

If a crank-rocker mechanism is used to drive the rear wheels of a bicycle, the rear wheels can complete one cycle. On one hand, if the crank is placed between the rear wheels, the propulsion of the rear wheels must be separate, or the pedal can be so close to the ground that becomes risky when it is in the lowest position. This can cause a balance problem on the vehicle due to the individual actuation of the wheels or crashing to any bulge on a road. On the other hand, if the crank is not placed between the rear wheels, then the user will have a distance between his/her legs. Thus, the effective force applied to the pedal will be decreased due to the direction of the legs. The direction of the legs must be vertical from the back view as shown in Figure 2. Moreover, this type of motion can cause disorders in knees.

Figure 2 – Back view of the motion of climbing stairs.

Double- rocker mechanisms provide an oscillatory motion as an output from an-other oscillatory motion as an input. In other words, when the rider drives the pedal, both the pedal and the output link will create an oscillatory motion. Thus, the linkage can be assembled between the rear wheels on the axel. Therefore, both pedal's mechanisms can drive the same axel. Moreover, the distance between the legs can be kept short enough to apply a vertical force on the pedal. Furthermore, both the double-rocker mechanisms can return the initial driving position without blocking the motion of rear wheels by using the ratchet mechanism used in traditional bicycles.

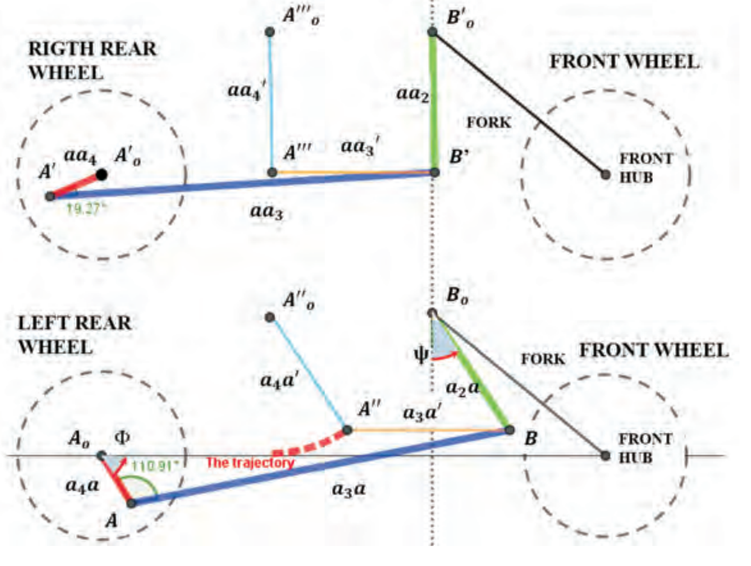

Figure 3 – The schematic mechanism for pedal drivetrain.

One of the most important issues is the balance of the rider despite of the three wheels of the bicycle. The pedaling process can be carried out by the force of weight and muscles as mentioned earlier. Thus, the weight will be on the right side of the bicycle for driving one of the pedals and subsequently will be on the other side of the bicycle for driving the pedal on the left. This motion can be synchronously directed reverse by the help of a bevel gear set. Yet this will cause a balance problem. The only way to balance this dynamic weight is imitation of the motion of climbing stairs. Therefore, there must be not only a short distance between the legs, but also a wide flat fricative surface underneath the foot or shoes. This surface must be parallel to the line between the hubs all along the pedaling process and move along a trajectory in the form of circular arc as shown in Fig. 3. The elements of the pedal double-rocker mechanism are aa2, aa3, aa4 which form the drivetrain in the place of chains in the right side of the bicycle, and a2a, a3a, a4a which form the drivetrain in the place of chains in the left side of the bicycle. The closed kinematic loops consisted of aa4', aa3', aa2 and a4a', a3a', a2a are parallel mechanisms which is in the place of pedal of traditional bicycles helping user's foot to move on a circler trajectory just like in climbing stairs by the help of the link aa3' and the link a3a'.

The user must put the foot on a higher and forward pedal for each drive cycle of the pedal just like in the motion of climbing stairs. As the body weight is loaded on the higher and forward pedal, the rear wheels can be driven forward by the help of the link aa4 or a4a rotating clockwise. The link aa4 and a4a are connected to the ratchet on the rear axle. Therefore, the mechanisms on both sides of the bicycle can rotate reverse directions. Moreover, this feature provides an uninterrupted drive for the rear axle. The fork connected to the steering wheel in front of the bicycle is shown in Figure 3. The fork is designed as an inclined position to allow steering wheel to turn right and left direction during the pedaling process(see the link of animation and 1, 2).

The pedal mechanism is driven by not only muscles of the leg but also by the body weight in the new concept. Therefore, the torque on the rear axle is important. The highest torque is expected to be obtained on the extreme position of the mechanism as shown in Fig. 4. In this analysis, only one of the pedal mechanisms is considered. The body weight is accepted as 800 Newton. The half of the total weight was ideally applied on the joint B'. The other half of the total weight is applied on the joint A''' which is helpful to find the magnitude of the load on the link aa'3. The link aa2 and aa'3 carry a tension load, as the link aa3 carries compression load. Thus, the static equilibrium equations on the joint B' can help to find the loads on aa2 and aa3. The angle μ is the transmission angle which is shown in the extreme point in Fig. 4. The extreme pedal height is 36 cm which is the same height of double steps of the standard stair.

The mechanism is optimized by using Microsoft Excel [30]. The torque as objective function is formulated by the help of static force analysis of the mechanism. The constraints are derived from the geometric limitation as shown in Fig. 3-4. The total length of bicycle is limited to 180 cm. The results are given in the table 1. The change of the angles Ψ, μ and torque T compared to the angle ϕ are given in the Fig.5. According to Fig.5, the maximum torque is about 90 Nm which means 600W energy can be produced with only 60 rpm speed.

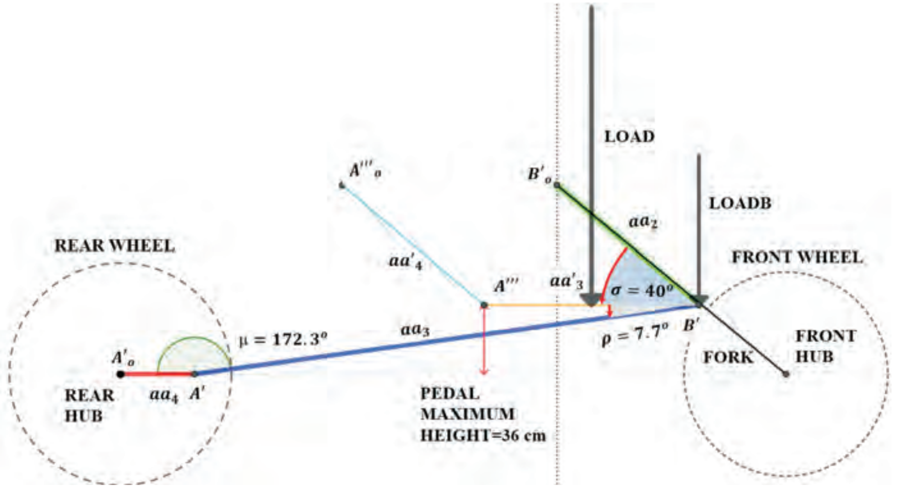

Figure 4 **–** The extreme position of the pedal mechanism.

Table 1 **–** The results of optimization

Links	aa1	aa2		aa3	aa4
Lengths (cm)	128.4	20		137.5	50

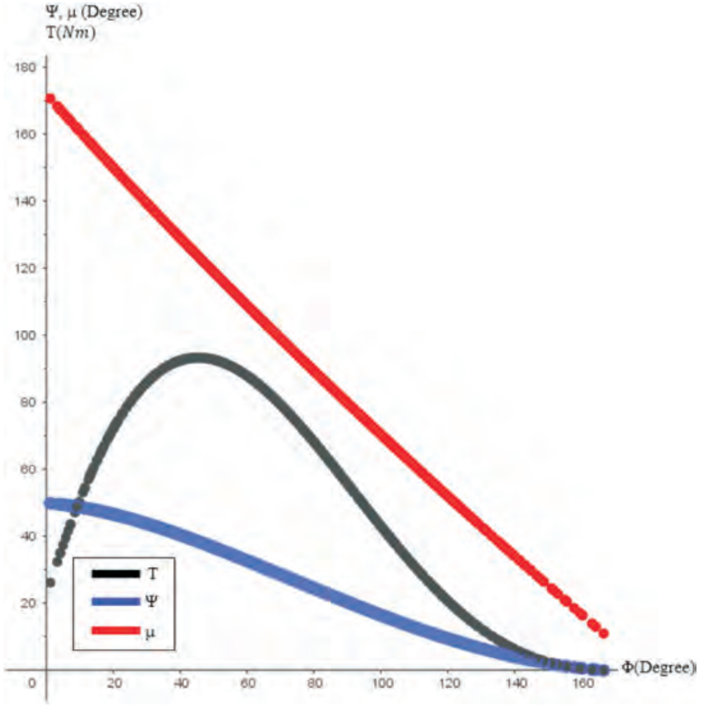

Figure 5 **–** The graphical illustration of changes in the values of Ψ and T compared to Φ.

An evaluation of mechanism design for pedal drivetrain was presented. The pedal design was concluded in the favor of double-rocker mechanism due to the design simplicity. A CAD model was designed. The CAD model was designed as a hybrid bicycle which can be pedaled or driven by an electrical motor in the front hub. This model shows a saddle which cannot be used during pedaling. The saddle is for resting when the electrical motor is activated. The geometrical constraints and difficulties of manufacturing were the main obstacles in elimination of crank-rocker mechanism. However, a design made of crank-rocker must have bigger height to exceed the geo-metric constraints. Therefore, rear wheels can have bigger diameters than standard wheels as it was designed in the past. Yet this paper targeted to design a new bicycle model by using mostly shelf-ready products. Although the study includes the very beginning research on the topic, a realistic evaluation is presented to attract attentions of researchers on the field of mechanism. So that, new designs in favor of user can be launched in the market.

The future of research in the topic will be on the multibody dynamics of the de-sign. Moreover, due to the bicycle pedaled upright, the aerodynamic efficiency must be researched. Furthermore, if the bicycle can be used to produce electricity , how much energy can be produced as the user commute in a city such as from home to job? What are the critical parameters to increase energy production from the bicycle? Can the design help to increase the distance of travel by only charging once in a day? What could be the effect of the new design on the user's health in long run? What muscles can be improved by the help of the new design? What are the harms of the new design in long run?

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