A BIOMECHANICAL ANALYSIS OF CONVENTIONAL AND NON-CONVENTIONAL BICYCLE PEDALING MECHANISMS

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The use of the bicycle extends far beyond modern recreation and sports racing events. Bicycle ergometers are widely used as testing devices to determine aerobic fitness levels and cardiac function. Over the past several years, pedal-powered vehicles and stationary bikes have increased in popularity. This has come about as a result of an increased public awareness of the health benefits of cardiovascular conditioning, as well as providing an alternative form of transportation. The latter deals with the development of the human powered vehicle (HPV) where efficiency of locomotion is of chief importance. The purpose of this paper is to study the efficiency of a conventional circular pedal motion (CPM) bicycle cyclist. Patello-femoral force is a contributing factor to chondromalacia-patella (Dickson, 1985) and is a concern in both locomotion and exercise/rehabilitation.

Research investigating the forces applied using conventional CPM systems is extensive (Gregor et al., 1985; Davis and Hull, 1981; Hull and Davis, 1981; Soden and Adeyefa, 1979; Hull and Jorge, 1985; and Newmiller et al., 1988). Reported movement patterns and applied forces at specific pedal positions are relatively consistent between studies. The less popular and less available NCPM system has not been studied extensively by the research community.

METHODS

The CPM system bike was made by Onivega with toe clips. The bike was mounted on a stationary trainer to allow video taping of simulated riding. The NCPM system was the Alenax Tramsbar Power bycicle. This system has two ratcheting sprockets, one on each side of the rear tire. One end of each of two chains is attached to one end of a pair of levers with pedals on the opposite ends of the levers. The levers reciprocate via a cable connecting the free ends of the chain. Because the chain cannot tolerate a compression along its long axis, no tension can be created by pulling the pedals up. No toe clips were needed because when one pedal is moved down the other moves up. The NCPM system bicycle was mounted on a motor driven treadmill to provide a riding simulation, and a shuttered video camera was used to film the subject completing ten stroke cycles on each system. Video prints were made at approximately 0.45 rad intervals of crank rotation. A theoretical model was developed and applied to both systems.

Joint moment arms were determined for the right ankle, knee and hip by analyzing x-rays of the subject's thigh, shank and foot segments. Instant centers of rotation were determined by the use of Moire fringes (Gertzbein, et al., 1985) and respective moment arms were measured from the x-ray film. These measurements are necessary to determine the work done by antagonistic muscle groups spanning more than one joint. This condition is referred to as Lombard's paradox (Lombard, 1903; Gregor, et.al., 1985). The muscles involved are the gastrocnemius, responsible for knee flexion and plantar flexion; biceps femoris, semimembranosus, and semitendinosus contributing to to knee flexion and hip extension; and the rectus femoris which is a knee extensor and hip flexor.

The contribution of each of these muscules was determined by estimating each muscle's maximum length of shortening and the amount of tendon displacement along the long axis of the muscle, as it moves from its resting length to its shortened length. Moment arms of the tendon were plotted against joint angle. The sum of the integrals of the equations fitting those curves was determined, from resting (0 rad) to the two respective joint angles. An assumption was made that muscle will shorten 2/3 of its resting length. The only muscle where tension was not exerted by the contracting muscle was the gastrocnemius at the 6° past top dead center (TDC) crank position in the CPM system bicycle.

Cross sectional areas of the two-joint muscles relative to the total cross sectional area of the total major muscle movers at the hip, knee and ankle were determined. The following assumptions were made: (1) The gastrocnemius tendon on the posterior femur was assigned a tension of 60% of the total force exerted by the major plantar flexors. (2) The rectus femoris provided 25% of the tension exerted by the knee extensors. (3) The sum of the gluteus maximus and the posterior portions of the gluteus medius and gluteus minimus exert three times as much force as the sum of the long head of the biceps femoris, semitendinosus and semimembranosus.

The model utilized for ideal force apllication for the CPM system is similar to one used by Soden and Adeyefa (1979). Their "ideal" condition did not allow for the shear force exerted by the foot on a pedal equipped with toe clips. They suggested that this force was not significant and could be omitted. Measurement techniques used by other investigators (Hull and Jorge, 1985; Davis and Hull, 1981; Hull and Davis, 1981 and Newmiller, et al.,1988) indicate otherwise. A mean peak value of the shear forces relative to normal pedal forces was determined to be 1:3 respectively. Observed crank arm torque approximates the following curve (Eq 1) where Y is the vertical force and θ is the displacement clockwise beginning at TDC.

$$\Gamma = Y \sin \theta \qquad (1)$$

The work done in one half pedal revolution was determined using one arbitrary unit of force. The crank arm was 18cm long but standardized to 1 length unit to simplify the calculation. Total work done is determined by solving the integral:

$$U_T = \int_0^{\pi} \sin \theta \, d\theta \qquad (2)$$

$$U_T = 2au \qquad (3)$$

The horizontal component is the shear force applied to the pedal. The force/ position curve was the absolute value of a cosine curve of 1/3 the amplitude of the peak vertical force. The total work done can be broken down into the following vertical and horizontal components:

$$U_H = 2 \int_{0.3217}^{\pi/2} 1/3 \cos \theta \, d\theta \qquad (4)$$

$$U_V = \int_0^{\pi} \sin \theta \, d\theta - 2/3 \int_{0.3217}^{\pi/2} \cos \theta \, d\theta \qquad (5)$$

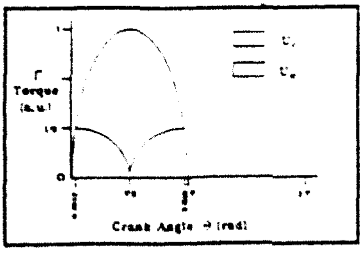

Figure 1: Torque/Crank Angle Curve.

Figure 1 shows the torque/position curve for the vertical and horizontal components. The same relationship was used to determine the vertical force on the NCPM system, using the observed lever arm limits. An assumption was made that there was no shear force, and the normal force had a vertical component that satisfies the following equation:

$$\Gamma = Z \sin \theta \qquad (6)$$

The work done in one pedal stroke of each respective pedalling system was determined by solving the integral:

$$U_T = \int_{\theta_1}^{\theta_2} Z \sin \theta \, d\theta = 2au \qquad (7)$$

Using the limits of the crank stroke for ϕ_1 and ϕ_2 as 1.431 and 2.758 respectively, the constant Z (peak torque) was solved.

$$Z \left(- \cos \theta \Big]_{1.431}^{2.758} \right) = 2au \qquad (8)$$

$$Z = 1.875 \qquad (9)$$

In both systems the work done in lifting the weight of the leg was omitted because that potential energy is released on the next stroke. Vertical travel of the leg's was considered not significantly different between the CPM and NCPM systems. Forces were solved conforming to the model described. Absolute pedal angle with respect to the horizontal φ was used in determing forces. Because the NCPM system had no toe clips, the assumption was made that all forces applied were normal to the pedal, and a frictional force was exerted to hold the foot on the pedal when small absolute angles φ existed. Equation 11 was substituted for F_V (vertical force) in equation 10. F_N (force normal to the pedal) was solved for using equation 12. Figure 2 shows the NCPM forces. Note that d is 1.757 times the one length unit used in the CPM system (Eq 1).

$$\Gamma = 1.875 \sin \theta = D \, F_V \sin \theta \qquad (10)$$

$$F_N \cos \theta = F_V \qquad (11)$$

$$F_N \; 1.875/1.757 \cos \varphi$$

$$F_N = 1.067/\cos \varphi \qquad (12)$$

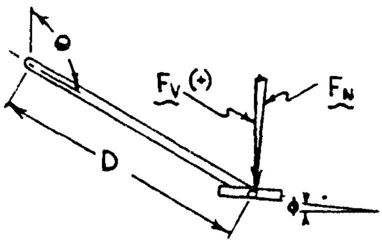

Figure 2: NCPM Pedal Forces.

The CPM system force components are solved for in a similar fashion except that now both shear and normal forces exist. Equation 13 was used to solve for the vertical force applied to generate the torque necessary at the crank arm.

Figure 3 details the normal and shear components of the vertical forces F_V.

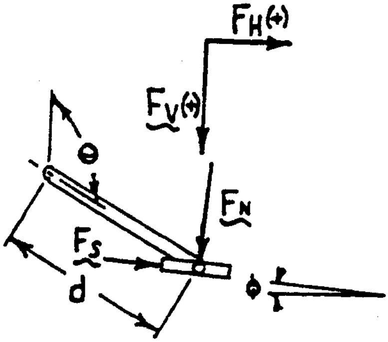

Figure 3: CPM Pedal Forces.

Equations 14 and 15 compensate for the absolute pedal angle. Equations 16 and 17 are equations 13 combined with 14 and 13 combined with 15 respectively; used to solve for normal vertical F_{NV} and shear vertical F_{SV} forces:

For : $0 < \theta < \pi$

$$F_n = F_v \cos \varphi \qquad (14)$$

$$F_s = F_v \sin \varphi \qquad (15)$$

$$1/d - 1/3d \tan \theta = F_n \cos \varphi \qquad (16)$$

$$1/d - 1/3d \tan \theta = F_s \cos \varphi \qquad (17)$$

$$F_{nv} = \cos \varphi/d - \cos \varphi/3d \tan \theta \qquad (18)$$

$$F_{sv} = \sin \varphi/d - \sin \varphi/3d \tan \theta \qquad (19)$$

The horizontal force F_H and components F_{NH} and F_{SH} were determined in the same manner with the exception that the direction of the force changes at $0 = \pi/2$. Following the convention established:

Since:

$$\Gamma = 1/3 \cos \theta = F_z d \cos \theta$$

$$F_{nx} = F_s \sin \varphi,$$

and $$F_{sx} = F_s \cos \varphi$$

Therefore: $$\sin \varphi/3d = F_{nx} \quad \text{for} : 0 \le \theta, \pi/2, \qquad (20a)$$

$$- \sin \varphi/3d = F_{nx} \quad \text{for} : \pi/2 < \theta \le \pi, \qquad (20b)$$

$$\cos \varphi/3d = F_{sx} \quad \text{for} : 0 \le \theta < \pi/2, \qquad (21a)$$

and $$- \cos \varphi/3d = F_{sx} \quad \text{for} : \pi/2 < \theta \le \pi \qquad (21b)$$

Table 1 presents the algebraic sum of all shear and normal forces. Normal and shear forces were calculated for the CPM and NCPM systems. Lines were drawn normal to the pedal and parallel to the surface of the pedal through its axis of rotation. External moments were measured from the perpendicular distance from the line to the center of rotation for éach of the three joints. A positive counterclockwise movement convention was established.

TABLE 1
Normal and shear forces for CPM system bicycle at various crank angles. (Normalized for crank length of I unit).

for θ:	$0 \le \theta < 0.3217$	$0.3217 \le \theta \le \pi/2$	$\pi/2 < \theta \le 2.820$,	$2.820 \le \pi$
F_s=	$\sin \varphi$	$\sin\varphi - (\sin\varphi/3\tan\theta) + \cos\varphi/3$	$\sin\varphi - (\sin\varphi/3\tan\theta) - \cos \varphi/3$	$-\sin \varphi$
F_s=	$\cos \varphi$	$\cos\varphi - (\cos\varphi/3\tan\theta) + \sin\varphi 3$	$\cos\varphi - (\cos\varphi/3\tan\theta) - \sin \varphi/3$	$\cos \varphi$

The resultant ankle moments were divided by the lever arm of the calcaneal tendon and multiplied by 0.60 to yield gastrocnemius tension. This tension multiplied by its lever arm at the origin at that knee angle, comprises an internal knee moment. The external hip moments were taken as the sum of 0.75 times the gluteus maximus lever arm and 0.25 times the biceps femoris, semitendinosus and semimembranosus lever arm. Total hip extension tension was determined and multiplied by 0.25 to determine the tension in this complex at the site of tibial insertion. That insertion's moment arm, at that joint angle, was measured and the product yielded a second internal knee moment.

From the sum of all moments acting on the knee, forces in the patellar ligament and quadriceps tendon were determined and 0.25 times this value, times the moment arm of rectus femoris at the acetabulum, produces another internal moment. The contribution of this new resultant moment on knee extension forces was recalculated until the discrepancy from the previous values was less than 5%. Figure 4 shows a free body diagram depicting all forces, other than gravity, acting on the leg

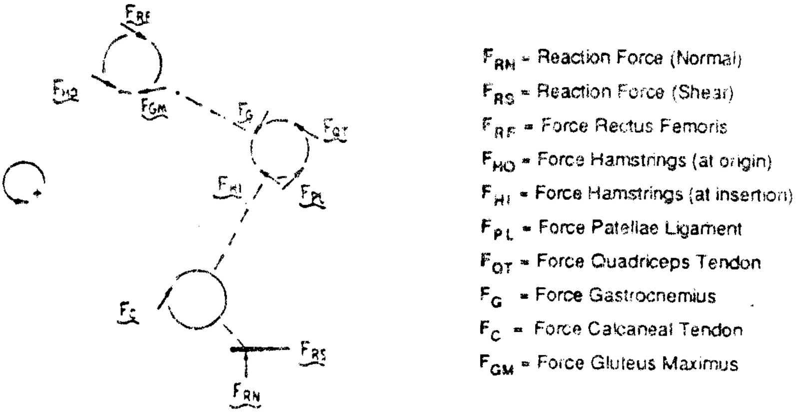

Figure 4: Forces applied and sign convention of moments about the hip, knee, and ankle (excluding body weight).

The resultant moment about each joint was determined at the selected joint angles. These values were plotted against joint angle and integrated over the initial to final joint angle values, taking into account any changes in direction encountered by the joints; observing eccentric contractions as well. Patellofemoral forces were calculated based on the tension values in the quadriceps tendon and the patellar ligament. This force is the algebraic sum of the products of tendon and ligament tensions and the cosine of the angles each of these vectors make with a line that passes through the point of contact of the patella and femur and the intersection of the two force vectors. (Ellis, et al., 1980). The sum of these two vector components was taken as the resultant compression patellofemoral force. These values were plotted and fitted with a smooth curve and integrated along the range of motion of the joint.

RESULTS

The total work done by the muscles of each joint is listed in Table 2. Figure 5 illustrates the stroking sequences in CPM and NCPM. The total work produced with the d now equal to 18 cm put into the original work equations 2 and 3 yielded a work product of 36 au (cm) for each 1/2 revolution. The data shows a 7% increase in the amount of work done in the conventional CPM system bicycle as computed to the NCPM system. The conventional

CPM system attributes 39.4% of the work produced by the muscles is due to Lombard's Paradox as compared to 26.9% in the NCPM system.

TABLE 2
Muscular work required to do 36 au cm of work for CPM and NCPM systems.

Joint	CPM (au·cm)	(Work Done)	NCPM (au·cm)	(Work Done)
	Value	%Total	Value	%Total
Hip	34.82	58.60	23.47	47.00
Knee Ext	14.38	24.30	15.32	31.10
Knee Flex	2.63	4.40	00.00	00.00
Ankle	7.55	12.70	10.46	21.20
Σ = (au · cm)	59.38	100.00	49.27	100.00

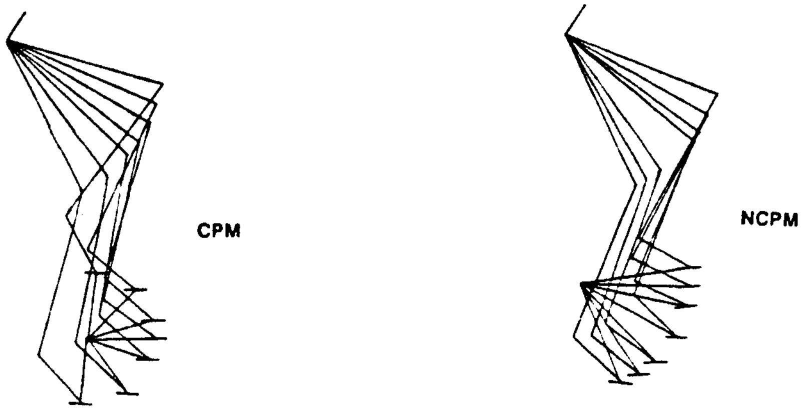

Figure 5: Stroking Sequences in CPM and NCPM.

Figure 6 shows the range of motion at the hip, knee and ankle for each type of pedal motion. This decrease in the joints use of available range of motion partially explains the smaller amount of antagonistic muscle action.

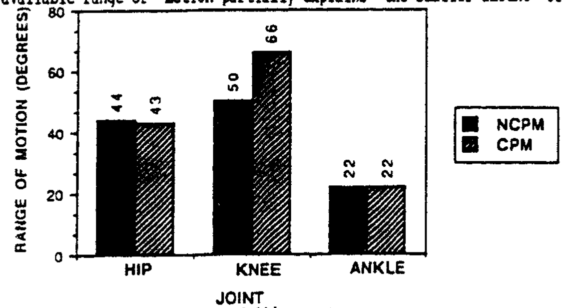

Figure 6: Joint Ranges of Motion for CPM and NCPM Pedalling Systems.

A comparison was made between these two bicycle systems based on the amount of work done relative to the crossectional area of the major muscles moves involved. Plagenhoef's data (1987) were used to determine total crossectional area of the major muscle movers for the joints analyzed. The data are recorded in Table 3.

TABLE 3:
Work output in CPM and NCPM systems.

Joint Action	Crossectional Area (cm^2)	% of Total	% Work Done CPM	Δ	% Work Done NCPM	Δ
Hip Extension	109.70	37.00	58.60	21.60	47.70	10.70
Knee Flexion	69.50	23.40	4.40	19.00	00.00	23.40
Knee Extension	71.10	24.00	24.30	0.30	31.30	7.10
Ankle Plantar Fl.	4.62	15.60	12.70	2.90	21.20	5.60
Σ				43.80		46.80

Patellofemoral forces were analyzed for one stroke cycle for both CPM and NCPM. The area under the curve for one stroke cycle was 2.486 total units with the NCPM system and 2.191 total units in the CPM system. This represents a 11.9% difference between the CPM and NCPM systems. Note that this force is applied through 0.87 rad. angular displacement on the NCPM system or 2.857 units force/rad. knee displacement and through 0.56 rad (3.91 units force/rad knee displacement) for the CPM system. There is a 27.0% decrease in patellofemoral forces per unit of area contacted in the NCPM in comparison to the CPM system.

DISCUSSION

The primary findings of this study suggest that a more efficient system of producing work may exist with the NCPM system as compared to a conventional CPM system. At very high pedal velocities this increased efficiency in the NCPM system may be lost because rotational kinetic energy is stored in the crank, pedals and lower extremities in a circular pedaling motion. In the NCPM system the mass must be accelerated and decelerated in order to change direction at the beginning and end of each stroke. If the forces required to cause these decelerations comes from muscle power, then efficiency is lost. It is possible that this energy could be transferred to the locomotion mechanism of the bicycle without exerting muscular force to change the direction of the movement. To alleviate this potential problem, very high pedal velocities should be avoided. As the pedal force is increased, the absolute patellofemoral force per pedal stroke also increases. If the power output required can be achieved by a low pedal force and velocity, the increased efficiency, found in this model, may hold true.

With respect to a mode of exercise, where prolonged high power outputs are not the issue the NCPM system may offer a practical alternative. For persons with a limited hip or knee range of motion, chondromalacia patella, or other limiting conditions, this pedalling system may prove advantageous. It is conceivable that a low mass lever driven system could be developed in order to satisfy both populations.
When using a bicycle for transportation and exercise, the elimination of detrimental stressed is of obvious benefit. The data suggest that a 26.9% decrease in force per unit of crossectional area exists at the patellofemoral joint in the NCPM in comparison to the CPM system. The larger more sporadic patellofemoral forces calculated in the CPM as compared to the NCPM system may also contribute to improper patellar tracking and excessive patellofemoral forces. Both of these may contribute to chondromalacia patellae. The data also suggest that both systems could possibly be improved by repositioning the pedal arm or crank to more equally use the body's natural strength potential. The advantage of a push-pull lever NCPM system offers a plausible alternative to conventional pedalling systems.

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