# MECHANICAL WORK AND COORDINATIVE PATTERN OF CYCLING: A LITERATURE REVIEW

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Review
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## Abstract:

In this review paper three models to calculate mechanical work, the pattern of joint power during steady-state cycling and some theories regarding energy transfer through the joints and coordinative pattern analysis by joint mechanical work distribution will be briefly presented. Finally, there will be a report on the effects of workload, pedaling cadence and saddle height management on joint mechanical work. The first result that emerges from the management of the workload is that the positive mechanical work produced by the joints increases which is mostly related to the concentric muscle contraction. The contribution of hip and knee joints seems to be different from the ankle joint with changes in workload during cycling because the ankle joint muscles should be tuned to optimize stiffness and maximize the effective transmission of mechanical energy to the crank. When changing pedaling cadence, the authors have only agreed with the unchanged contribution of the ankle joint to the total mechanical work, while the hip and knee contribution results differ in the reported research. Lack of evidence in ankle joint function when the resistive force and pedaling cadence relationship are changed during fatigue as the mechanical energy transfer and stiffness function need further research. Controversial results have been reported in the analysis of joint contribution to the total mechanical work for different cycling expertise. Unfortunately, we cannot find conclusive research regarding the effects of saddle height on coordinative pattern mainly based on simultaneous analysis of joint moment distribution, joint kinematics and joint reaction forces.

***Key words:*** *joint mechanical work, lower limb joints, ankle joint, inverse dynamics, simulation models*

## Introduction

Bicycles have been largely used as a common way of transportation by many people around the world. An analysis of the pedaling movement helps engineers and researchers understand the complex cyclist-bicycle (Burke & Pruitt, 2003). Studies with different aims, including injury prevention (Asplund & St. Pierre, 2004; Wanich, Hodgkins, Columbier, Muraski, & Kennedy, 2007), muscle recruitment (Baum & Li, 2003; Bini, Carpes, Diefenthaeler, Mota, & Guimarães, 2008), pedaling technique (Coyle, et al., 1991; Rossato, Bini, Carpes, Diefenthaeler, & Moro, 2008), and energy expenditure (Hamley & Thomas, 1967; McCole, Claney, Conte, Anderson, & Hagberg, 1990) have contributed to improving cyclists' performance.

Regarding energy expenditure, we can observe that the mechanical characteristics (i.e. geometry) of a bicycle have been advanced in an attempt to reduce energy cost, improve transportation velocity, and increase movement economy (Minetti, Pinkerton, & Zamparo, 2001). In human locomotion, the concept of cost of transportation has been analyzed during walking and running with the purpose of understanding movement economy in different types of human locomotion (Saibene & Minetti, 2003). Minetti, et al. (2001) reported that bicycle design has been improved over the years in an attempt to reduce the cost of transportation and to increase movement economy. Kautz (1994) has also described that different chain rings affect the angular velocity of the crank-arm and the mechanical work produced to move the legs (i.e. internal work). These and other studies (Hamley & Thomas, 1967; McCole, et al., 1990) suggested that bicycle equipment has an important effect in mechanical work and energy expenditure during cycling.

Mechanical work during cycling should be also analyzed in relation to the improvement of movement economy by the analysis of coordinative pattern (Ericson, 1988; Ettema, Loras, & Leirdal, in press; Mornieux, Guenette, Sheel, & Sanderson, 2007; Sanderson, Mornieux, Guenette, & Sheel, 2008). Optimization of muscular function has been proposed as an effective solution in an attempt to improve the balance between mechanical work and metabolic energy (Nigg, Stefanyshyn, & Denoth, 2000). The complete comprehension of the central nervous system's control of muscle force production (i.e. coordinative pattern) still remains unclear (Kautz, Neptune, & Zajac, 2000) but several improvements have been achieved.

In this regard, we will briefly review three models to calculate the mechanical work, present joint power during steady-state cycling and some theories regarding energy transfer through the joints and coordinative pattern analysis by joint mechanical work distribution. Finally, we will report on the effects of workload, pedaling cadence, and saddle height management on joint mechanical work in an attempt to provide a practical application of energetic knowledge to performance.

To collect papers related to the main issue of this review we employed a computer search in some of the most used databases or aggregators (MEDLINE, SCOPUS, ISI Web of Knowledge, EBSCO, and GOOGLE SCHOOLAR) in addition to manual journal searches. All peer-reviewed journals, books, theses, and conference proceedings have been included in the databases search since 1960. The key words for our search were: 'muscle mechanical work', 'coordinative pattern', 'joint power', 'saddle height', 'workload', and 'pedaling cadence'. We have included the keyword 'cycling' and 'lower limb' in the "search within results" as a filter to exclude papers which do not concern cycling research. Articles were not included when: (1) they have been retrieved without, at least, an English abstract; (2) they concerned the analysis of types of upper body mechanical work, and (3) they have been published in non-scientific or non peer-reviewed journals.

## Models to calculate mechanical work

Several models have been presented in an attempt to calculate mechanical work during cycling (Hansen, Jørgensen, & Sjøgaard, 2004; Kautz, 1994; Neptune & van den Bogert, 1998). As van Ingen Schenau and Cavanagh (1990) and Nigg et al. (2000) have explained in detail most of the models to calculate mechanical work, we will briefly review some of them.

Based on the changes of kinetic and potential energies of each segment (i.e. internal work), the model proposed by Fenn (1930a, 1930b) has been adapted through the years (Aleshinsky 1986a, 1986b, 1986c, 1986d, 1986e; Winter, 1979). These models (kinematic models) have been recently compared by Hansen, et al. (2004) in an attempt to understand the behavior of internal work during cycling. The authors reported that the selected kinematic models to calculate mechanical work during cycling affect the final results of internal work determination. Nigg, et al. (2000) have also indicated that based on the limitations of the proposed models, most results have been overinterpreted. Basically, these limitations are (1) the assumption of no-energy transfer between the segments and (2) kinematics data processing errors.

Elftman (1939) reported another approach to calculate joint mechanical work, which uses the resultant joint moments and angular velocity to compute each joint power (kinetic model). It has been also applied to compute mechanical work during cycling (Broker & Gregor, 1994; Ericson, 1988; Neptune & van den Bogert, 1998), but as reported for kinematic models, most of its results have been overinterpreted (Nigg, et al., 2000). The limitation of the kinetic model is based on the inverse dynamics approach, which does not concern the effects of co-contraction on joint moments (Neptune & van den Bogert, 1998).

In this regard, a more complex model has been proposed to calculate mechanical work during cycling by Neptune and van den Bogert (1998), which includes the force-length-velocity characteristics of 28 muscles through computational simulation. It has been indicated as the most sensitive model for the comprehension of muscle coordination during cycling, mainly because it takes into account muscle co-contraction (Erdemir, McLean, Herzog, & van den Bogert, 2007; Kautz, et al., 2000). Unfortunately, most available results from the simulation model only reported steady-state cycling conditions (Neptune & van den Bogert, 1998; Kautz & Neptune, 2002; Zajac, 2002; Zajac, Neptune, & Kautz, 2002). Research concerning simulation model is different from steady-state and will be presented in the following contents of this paper. It is also important to address the fact that simulation models have limitations related to assumptions of anatomical (i.e. moment arm), muscular (i.e. pennation angle), and joint characteristics (i.e. joint axis of rotation) which would overestimate the muscle force calculations (Erdemir, et al., 2007; Zatsiorsky, 1998).

## Joint power during steady-state cycling

Most of the data presented in literature regarding joint power have been developed by conventional inverse dynamics data (kinetic model), which has been an input variable for the simulation model. In Figure 1, ankle, knee and hip joint power of eight cyclists is depicted (unpublished data), pedaling at 269±20 W at preferred cadence (92±11 rpm).

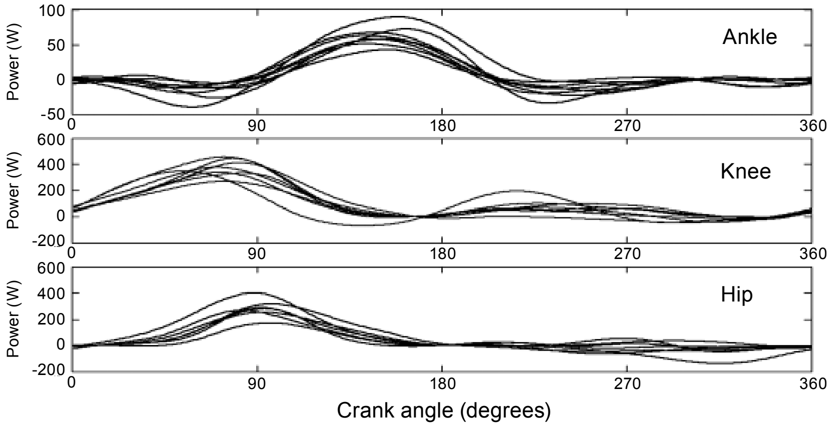

*Figure 1. Ensemble ankle, knee and hip joint power from eight cyclists pedaling at 269±20 W of workload and 92±11 rpm of preferred pedaling cadence.*

As previously reported by Broker and Gregor (1994), most of the mechanical work generated by joint power occurred in the power phase of the crank cycle (0 – 180° of crank angle). Contrary to walking and running, most of the mechanical energy related to cycling movement is provided by the concentric actions of the lower limb muscles (Kautz & Neptune, 2002; Williams, 1985). We can observe this by the small negative power in all three lower limb joints in Figure 1, as the hip and knee joint power were higher than the ankle joint. Therefore, Hawkins and Hull (1990) conducted a computational simulation to calculate the mechanical work developed by some of the most important muscles of cycling movement. Their concern was on the occurrence of stretch-shortening cycles (eccentric followed by concentric contraction) during cycling, which was observed to occur at the hip joint extensors (i.e. *m. gluteus maximus* and *m. biceps femoris*) and knee joint extensors (i.e. *m. vastus lateralis* and *m. rectus femoris*). Results indicate that the storage of elastic energy, even lower than in running, could be observed during cycling. Sanderson, Martin, Honeyman, & Keefer, 2006) reported that the *m. soleus* worked eccentrically at the recovery phase of pedaling cadence while *m. gastrocnemius* acted concentrically, also presenting evidence of eccentric contraction during the cycling movement. In Figure 2, we summarize in six events the ankle joint muscles' storage and release of energy during the power phase of crank cycle.

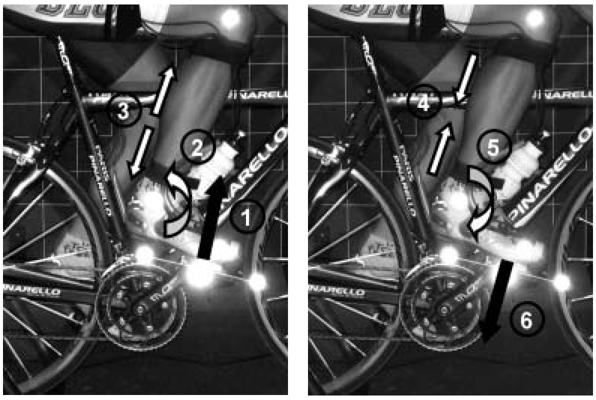

*Figure 2. Representative illustration of the series of events related to mechanical energy storage (a) and release (b) during the power phase of crank cycle. Pedal reaction force (1) generates flexor moment in the ankle joint (2) which increases plantar flexor muscles' length (3). After the storage of energy by the eccentric contraction (event 3), the release of this energy starts with a concentric contraction of plantar flexors (4) which changes the ankle joint moment to plantar flexors (5) and increases pedal force application through the power phase of crank cycle (6).*

The energy storage introduced in Figure 2 can be observed in Figure 3 by the ankle angle and the resultant moment analysis during the power phase of crank cycle.

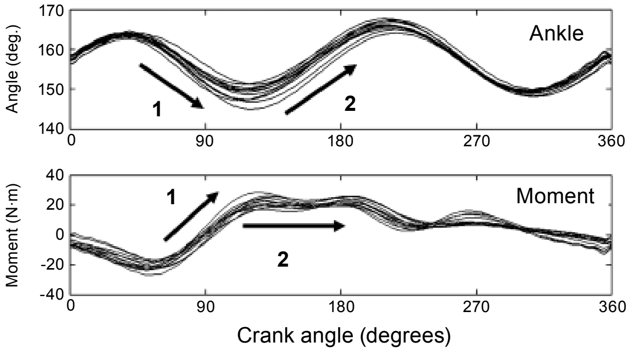

*Figure 3. Fifteen cycles of ankle joint angle and resultant moment of one cyclist at 397 W of power output and 105 rpm of pedaling cadence. For ankle angle, increased values indicate increased plantar flexion while for resultant moment positive values indicate the plantar flexor moment. Event 1 indicates increased dorsiflexion associated with increasing plantar flexion moment while event 2 indicates increased plantar flexion with maintenance of plantar flexion moment.*

In Figure 3, we can observe two events related to storage and release of mechanical energy by the plantar flexor muscles. Data were analyzed based on previous studies by Bini, Diefenthaeler, and Mota (in press) and Dingwell, Joubert, Diefenthaeler, & Trinity (2008). During event 1, the increased dorsiflexion associated with increased plantar flexor moment indicates triceps surae increasing in length while this muscle group increases the plantar flexor moment. During the second event, the ankle joint moves to the plantar flexion while the resultant moment is also plantar flexor. This second event is associated with energy transfer from proximal segments, which will be introduced in the following contents.

## Mechanical energy transfer through joints and coordinative pattern

As a multi-joint closed kinetic chain exercise, cycling has been proposed to evolve force and power transfer through the hip, knee and ankle joints (van Ingen Schenau, Boots, de Groot, Snackers, & van Woensel, 1992). We selected three studies on this issue (Broker & Gregor, 1994; Fregly & Zajac, 1996; Neptune, Kautz, & Zajac, 2000) based on their different methodological approaches.

Broker and Gregor (1994) performed the analysis of energy transfer through the joints using a kinetic model of mechanical energy. They reported an increase of power transfer of distal segments in comparison to proximal segments (i.e. low energy transfer from pelvis to thigh in relation to energy transfer from shank to the foot). The limitation of the kinetic model applied by Broker and Gregor (1994) was the same as the conventional kinetic model, as previously reported.

Fregly and Zajac (1996) conducted a simulation model using only kinematic data (see Fregly and Zajac, 1996 for further details regarding the model), in which they improved the possible analysis of energy transfer. The authors presented data concerning the contribution of each joint and the contribution of inertial properties to mechanical energy transfer. They also observed an increased function of the hip and knee joints to power production while the ankle joint has been related to higher energy transfer (than generation) to the crank.

Neptune, Kautz, & Zajac (2000) conducted a simulation model for the analysis of the most important muscle groups related to cycling movement. The authors reported positive and negative muscle work for the Vastii group, GMax group (hip joint extensors), PSOAS group (hip joint flexors), *m. biceps femoris* short head, *m. rectus femoris,* hamstrings group, *m. soleus, m. gastrocnemius* (both heads), and *m. tibialis anterior.* Their results allowed us to understand that ankle joint muscles (*m. soleus, m. grastrocnemius* and *m. tibialis anterior*) have an important function in the mechanical energy transferred from the limbs to the crank, while Vastii and GMax group have been related to mechanical energy generation.

By studying the independent contributions of muscle groups during cycling, we can better understand the coordinative pattern. Two recent studies have investigated coordination in this manner. Mornieux, et al. (2007) conducted an analysis of joint moment distribution during cycling in hypoxic conditions in an attempt to understand joint contributions and to infer the coordinative pattern. They reported that hypoxia situation does not affect joint moment distribution. Hoshikawa, Takahashi, Ohashi, & Tamaki (2007) compared joint mechanical work distribution of cyclists and non-cyclists in four different pedaling cadences (40, 60, 90, and 120 rpm). The results demonstrated that ankle and hip contribution to the total joint mechanical work (sum of ankle, knee and hip joint mechanical work) was reduced in cyclists compared to non-cyclists. An attempt to describe the coordinative pattern during cycling has been conducted earlier by Ericson and Nisell (1988), but only Mornieux, et al. (2007) and Hoshikawa, et al. (2007) introduced the study of the coordinative pattern during cycling by the analysis of mechanical work or joint moment distribution.

Even with limitations on the method of analysis (kinetic model), Mornieux, et al. (2007) indicated that the manipulation of mechanical and physiological variables should not modify joint moment distribution. However, Hoshikawa, et al. (2007) observed that the cycling experience and pedaling cadence should affect the coordinative pattern. Chapman, Vicenzino, Blanch, & Hodges (2007) described the differences in muscle activation pattern for cyclists and non-cyclists, which reported the effect of the experience on cycling skills. Hasson, Caldwell, & van Emmerik (2008) presented evidence of changes in net joint moment and muscle activation during cycling after pedaling technique training, which has an effect on the coordinative pattern. In this regard, we cannot be sure that cycling is a robust motor pattern as previously proposed (Mornieux, et al., 2007).

The next three sections will be concerned with the effects of some usual mechanical management in joint power production and coordinative pattern. Unfortunately, we will be able to observe that there are still gaps in the comprehension of coordinative pattern during cycling (i.e. fatigue) and that there are few studies on this issue.

Based on the previous contents and in the summary of results reported in Table 1, we can observe that different models have been applied to analyze mechanical work during cycling which limits a comparison of results. Only Neptune and van den Bogert (1998) compared the different methods to compute mechanical work during steady-state cycling, which also suggests further research on this issue. Comparison and validation of models require *in vivo* measurements of muscle or tendon forces Erdemir, et al. (2007) which increases the complexity of these studies.

*Table 1. The mechanical energy transfer through joints and coordinative pattern during cycling*

| **Publication** | **Type** | **Subjects** | **Findings** | **Applied model** |
|---|---|---|---|---|
| Ericson (1988) | Original | Six healthy subjects | Hip and ankle extension work proportionally decreased with increased work-load. | Kinetic |
| Broker & Gregor (1994) | Original | 12 elite cyclists | The knee joint dominated (>50%) in contributing to system energy and a moderate amount of energy was derived from hip joint reaction forces (>6%). | Kinetic |
| Van Ingen Schenau, et al. (1992) | Original | Five trained cyclists | The results show that the transfer of the hip, knee and ankle joints into the translation of the pedal is constrained by conflicting requirements. | Kinetic |
| Fregly & Zajac (1996) | Original | - | Net ankle and hip extensor joint torques function 'synergistically' to deliver energy to the crank during the downstroke. The net hip extensor joint torque generates energy to the limb, while the net ankle extensor joint torque transfers this energy from the limb to the crank. The net ankle joint torque transfers and the net knee joint torque generates energy to the crank by contributing to the driving component of the pedal reaction force. | Simulation |
| Neptune, et al. (2000) | Original | - | The *rectus femoris* used complex biomechanical mechanisms including negative muscle work to accelerate the crank. The negative muscle work was used to transfer energy generated elsewhere (primarily from other muscles) to the pedal reaction force in order to accelerate the crank. | Simulation applied on previous experimental data |
| Mornieux, et al. (2007) | Original | Seven trained cyclists | The relative ankle moment of force remained at 21% regardless of manipulation. The relative hip moment was reduced on average by 4% with increased cadence and increased on average by 4% with increased power output whereas the knee moment responded in the opposite direction. These results suggest that the coordinative pattern in cycling is a dominant characteristic of cycling biomechanics and remains robust even in the face of arterial hypoxemia. | Kinetic |
| Hoshikawa, et al. (2007) | Original | Seven cyclists and five healthy subjects | The average relative contributions of the knee were decreased, while those of the hip were increased at the pedaling cadences increased. Those relative values of the ankle and hip joint for cyclists were significantly lower than those for non-cyclists at almost all pedaling cadences. On the other hand, those relative values of the knee for cyclists (CY) were significantly higher than those for non--cyclists (NC) at all pedaling conditions. | Kinetic |
| Hasson, et al. (2008) | Original | Nine healthy subjects | After a single practice session, the error between the applied and target pedal force directions decreased significantly. This improved performance was accompanied by a decrease in ankle plantar flexor torque and an increase in knee and hip flexor torques. The monoarticular muscles exhibited greater alterations, and appeared to contribute to both mechanical work and force-directing. | Kinetic |

## Effects of workload on joint mechanical work and coordinative pattern

The first result that emerges from the management of workload is that the positive mechanical work produced by the joints increases (Ericson, 1988), which is related to the concentric muscle contraction. Regarding the different contributions of ankle, knee and hip joints to workload increases, Ericson and Nisell (1988) reported that all joints have increased their mechanical work, while Broker and Gregor (1994) reported small changes for the ankle joint with an increase of the workload. In this regard, Gonzalez and Hull (1989) have previously indicated that the majority of the propulsive force generated is developed by the hip and knee joints.

Broker and Gregor (1994) have also reported that 6% of the knee joint's mechanical work is related to the transfer of mechanical energy from the hip joint. Biarticular muscles (Hof, 2001; van Ingen Schenau, Pratt, & Macpherson, 1994) and intersegmental joint forces (Fregly & Zajac, 1996) are related to the force transfer through the lower limb segments.

As the main link between the propulsive joints (hip and knee) and the crank, the ankle joint has been the subject of research. Cannon, Kolkhorst, and Cipriani (2007) measured the gross efficiency (ratio between mechanical energy production and energy expenditure) and EMG of *m. vastus lateralis*, *m. gastrocnemius lateralis*, *m. biceps femoris*, and *m. tibialis anterior*. The authors compared three pedaling techniques: (1) preferred ankle position; (2) pronounced dorsiflexion; and (3) pronounced plantar flexion. The authors reported a reduction in the gross efficiency (2.6%) and an increase in *m. gastrocnemius lateralis* activation. These results can be explained by changes in the ankle joint muscles' length and force production with the shift in ankle joint position. Foot position during crank cycle has been reported to be important for the effectiveness of pedal force application (Korff, Romer, Mayhew, & Martin, 2007) and also for the optimization of force transfer of mechanical energy from the limbs to the crank (Raasch & Zajac, 1999; So, Ng, & Ng, 2005).

Even with the evidence reported by Cannon, et al. (2007) and Korff, et al. (2007) of the ankle joint position effects on cycling mechanics, there are also few studies regarding ankle joint contribution to the total mechanical work with the management of workload. Sanderson, et al. (2008) reported that ankle joint mechanical power remained unchanged with the increase of workload (150, 250, and 350 W), while the hip increased and the knee reduced their contribution to the total joint mechanical work. As reported by Mornieux, et al. (2007), the contribution of hip and knee joints seems to be different from the ankle joint with changes in workload during cycling, because the ankle joint muscles should be tuned to optimize stiffness and maximize effective transmission of mechanical energy to the crank.

There are also few studies with evidence regarding the effects of maximal situations on the joint mechanical work during cycling (i.e. fatigue). Sanderson, et al. (2008) evaluated subjects pedaling in a hypoxia situation, while they have calculated ankle, knee, and hip joints mechanical power. The authors observed that joint mechanical power distribution was not affected by hypoxia. Their hypothesis was that during maximal conditions (i.e. hypoxia) there are no differences in the motor pattern during cycling as proposed by Mornieux, et al. (2007) and Sanderson, et al. (2008). Unfortunately, only Mornieux, et al. (2007), based on Sanderson and Black (2003) results, reported that during fatigue situations there is no change on the joint moment distribution. However, they have not reported any additional explanation for the unchanged coordinative pattern while the joint kinematics and pedal force application have been modified (Amoroso, Sanderson, & Henning, 1993; Black, Sanderson, & Hennig, 1993; Sanderson & Black, 2003), and pedaling cadence seems to be reduced (Lepers, Hausswirth, Maffiuletti, Brisswalter, & van Hoecke, 2000; Lepers, Maffiuletti, Rochette, Brugniaux, & Millet, 2002) during a fatigue situation. Therefore, Bini, et al. (in press) described a reduced contribution of the ankle joint contribution to the total joint moments. Their results indicated that coordinative pattern is modified during fatigue based on the changes in joint moment distribution and altered kinematics pattern.

Workload effects during fatigue based on changes in the mechanical balance between resistive forces and pedaling cadence for the same power output are not clear. Controversial effects of fatigue in joint moment distribution have been reported (Bini, et al., in press; Mornieux, et al., 2007). We can also include the existing lack of evidence in the ankle joint function during fatigue during cycling. Mechanical energy transfer and stiffness needs to be addressed by future studies in cycling in fatigue situations.

## Effects of pedaling cadence on joint mechanical work and coordinative pattern

Analysis of pedaling cadence effects on joint mechanical work has been also conducted as an attempt to understand the coordinative pattern during cycling (Sanderson, et al., 2008). When power output is not fixed and pedaling cadence is increased, there is a higher joint mechanical work due to the increased internal and external work (Hansen, et

*Table 2. Summary of the publications related to the effects of workload on joint mechanical work and coordinative pattern*

| Publication | Type | Subjects | Findings | Applied model |
|---|---|---|---|---|
| Gonzalez & Hull (1989) | Follow up from previous data | Three healthy men | The major propulsive force generation has been developed by the hip and knee joints. | Kinetic |
| Amoroso, et al. (1993) | Original | 11 competitive cyclists | Fatigue resulted in greater hip extension with more noticeable observed at the ankle joint (greater dorsiflexion). No effects on force effectiveness. Higher normal and shear forces on the pedal which might suggest adaptations of the joint moments and muscle activation | Partial Kinetic (only pedal forces) |
| Black, et al. (1993) | Original | 5 trained cyclists | Increased effectiveness of pedal forces by modified pedal force components (normal and shear) and pedal kinematics. Higher ankle dorsiflexion which might suggest adaptations of the joint moments and muscle activation | Partial Kinetic (only pedal forces) |
| Raasch & Zajac (1999) | Original | - | One pair of the groups (uniarticular hip and knee extensors) generates the energy required for limb and crank propulsion. The ankle plantar flexors transfer the energy from the limb inertia to the crank during the latter part of limb extension and the subsequent limb extension-to-flexion transition. | Simulation on previous experimental data |
| Sanderson & Black (2003) | Original | 12 competitive cyclists | There were changes in the pattern of force application, joint kinematics and joint moments of force as fatigue effects. Contrary to our initial assumptions, it would appear that riders became less effective during the recovery phase, which increased the demand for forces during the propulsive phase. | Kinetic |
| So, et al. (2005) | Review | - | In the power phase the hip, knee and ankle joints extend simultaneously for the pushing action, whilst in the recovery phase, they flex together to pull the pedal back to the top dead center of the crank cycle. Recent studies have indicated that in this repeated sequence, the monoarticular muscles are mainly involved in the generation of positive work whereas the biarticular muscles are responsible for regulating force transmission | - |
| Cannon, et al. (2007) | Original | 11 trained cyclists | Gastrocnemius EMG activity was higher with the dorsiflexion technique than when using the self-selected control position and decreases gross efficiency (GE). | EMG |
| Korff, et al. (2007) | Original | Eight cyclists | When the participants were instructed to pull on the pedal during the upstroke, mechanical effectiveness was greater and gross efficiency was lower. Mechanical effectiveness and gross efficiency during the circling and pushing conditions did not differ significantly from the preferred pedaling condition. | Partial Kinetic (only pedal forces) |
| Sanderson, et al. (2008) | Original | Seven trained cyclists | The ankle joint remained insensitive to all manipulations but the hip and knee joints appeared to interact in such a way that they compensated for changes in each other as a means to maintain each other as a way of providing the needed pedal force. | Kinetic |
| Bini, et al. (in press) | Original | Ten cyclists | Decreased ankle moment contribution to the total joint moments at the end of the test. The total absolute joint moment, and the hip and knee moments also increased with fatigue. Resultant force was increased, while kinematics has changed in the end of the test for hip, knee and ankle joints. | Kinetic |

al., 2004). For the same power output, increased internal work with the increase of pedaling cadence has been associated with the negative power produced by eccentric contractions (Ericson & Nisell, 1988) in an attempt to control force application to the pedals (Neptune & Herzog, 1999). Ettema, et al. (in press) reported that the increase of pedaling cadence results in a shift of the joints' peak power to a later instant of crank cycle due to an unchanged electromechanical delay (Li & Baum, 2004).

Hansen & Ohnstad (2008) reported that pedaling cadence is set by robust neural networks and it is unchanged when the physiological or mechanical load increases. Moreover, Candotti, et al. (in press) observed that pedaling cadence manipulation (60, 75, 90, and 105 rpm) does not affect the co-contraction of the *m. rectus femoris-m. biceps femoris*, or the *m. vastus lateralis-m. biceps femoris* muscles pairs of well-trained cyclists. Ettema, et al. (in press) have also suggested that pedaling cadence is chosen to fit the best relationship between force production and muscle shortening velocity. This should be indirectly observed in MacIntosh, Neptune and Horton (2000) results, who described an increase of the optimal pedaling cadence (based on muscle activation) for higher workloads.

While small changes in pedaling cadence (from 90 to 100 rpm) do not seem to affect joint mechanical work distribution (Broker & Gregor, 1994), wide ranges of pedaling cadence seem to change (Hoshikawa, et al., 2007; Sanderson, et al., 2008) or do not affect (Ericson, 1988) the contribution of the hip, knee, and ankle joint to the total mechanical work. As we should expect an increased contribution of inertial forces to joint mechanical work at higher pedaling cadence, Neptune and Herzog (1999) and Sanderson, et al. (2008) observed an increased contribution of the knee joint and a reduced contribution of the hip joint to the total joint mechanical work. This increased contribution can also be related to force transfer by biarticular muscles from the thigh to the shank (Hof, 2001; van Ingen Schenau, et al., 1994). However, Hoshikawa, et al. (2007) observed opposite results with the manipulation of pedaling cadence, and Ericson (1988) reported no effects of pedaling cadence on the joint

*Table 3. Summary of the publications related to the effects of pedaling cadence on joint mechanical work and coordinative pattern*

| Publication | Type | Subjects | Findings | Applied model |
|---|---|---|---|---|
| Ericson & Nisell (1988) | Original | Six heathy subjects | There were no significant changes on the force effectiveness due to alterations of the pedaling rate. | Partial kinetic (only pedal forces) |
| Neptune & Herzog (1999) | Original | Eight cyclists | There was no negative muscular crank torque generated at 60 rpm and negligible amounts at 75 and 90 rpm. But substantial negative muscular crank torque was generated at the two highest pedaling rates (105 and 120 rpm) that increased with the increasing pedaling rates. | Simulation applied on experimental data |
| MacIntosh, et al. (2000) | Original | Eight male subjects | When all seven muscles were averaged together, there was a proportional increase in EMG amplitude each cadence as power increased. The minimum EMG amplitude occurs at a progressively higher cadence as power output increases. | EMG |
| Hansen, et al. (2004) | Original | 16 healthy subjects | Results showed that internal power (IP) was statistically different between the kinematic models applied. IP increased significantly with the pedal rate - leg movements accounting for the largest fraction. | Kinematic |
| Ettema, et al. (in press) | Original | Ten competitive cyclists | The differences reported indicate the potential effect of inertia of the lower limb in phase shifts from joints to crank. Furthermore, the differences between the various crank variables indicate a change of technique with cadence. | Kinetic |
| Candotti, et al. (in press) | Original | Nine cyclists and eight triathletes | Pedaling cadence manipulation (60, 75, 90, and 105 rpm) does not affect co-contraction of the *rectus femoris-biceps femoris*, and *vastus lateralis-biceps femoris* muscles pairs of well-trained cyclists | EMG |

mechanical work distribution. All authors have only agreed with the unchanged contribution of the ankle joint to total mechanical work.

Hoshikawa, et al. (2007) presented evidence that the cycling experience affects joint mechanical work distribution, which re-enforces the results observed by Chapman, et al. (2007) where the muscle recruitment pattern is affected by the cycling experience. These results would give an explanation for the differences observed in joint mechanical work distribution reported in literature (Hoshikawa, et al., 2007; Sanderson, et al., 2008).

For pedaling cadence effects, controversial results have been reported in the analysis of joint contribution to total mechanical work. Hoshikawa, et al. (2007) introduced evidence that cycling expertise would affect joint contribution and coordinative pattern when pedaling cadence changes. More studies should be conducted with the focus on mechanical adaptation of different groups sorted by cycling expertise when pedaling cadence is modified.

## Effects of saddle height on joint mechanical work and coordinative pattern

The management of saddle height has been conducted with the propose of describing the pattern of joint load (Ericson & Nisell, 1987), since it has been reported that most injuries in cycling practice are related to bad positioning on the bike (Asplund & St. Pierre, 2004; Wanich, et al., 2007). In this regard, joint mechanical power distribution was analysed when the saddle height was 6 cm lower (Horscroft, Davidson, McDaniel, Wagner, & Martin, 2003). The authors reported that joint power distribution was not affected by saddle height reduction. It does not seem plausible that coordination pattern remains constant with the alterations in saddle height as the pedaling technique (Diefenthaeler, et al., 2006; Ericson & Nisell, 1988), muscle activity (Ericson, Nisell, Arborelius, & Ekholm, 1985), and joint kinematics (Nordeen Snyder, 1977) have been reported to change.

Hamley and Thomas (1967), and Shennum and DeVries (1976) described an optimal saddle height based on a reduced oxygen uptake. The lower oxygen uptake was previously related to optimal phenomena (Cavanagh & Kram, 1985), in which muscle force-length relationship and movement economy would be optimized. However, only Horscroft, et al. (2003) reported the effects of changing the saddle position on joint mechanical power. Gonzalez and Hull (1989) conducted a multivariable computational optimization based on an attempt to reach a lower sum of hip and knee joint moments. They observed the saddle height effects on hip and knee joint moments.

Unfortunately, we cannot find any research regarding the effects of saddle height on joint mechanical work distribution, neither with simulation models to analyze muscle force production. Herewith, only EMG data has been reported in an attempt to understand the coordinative pattern during cycling at different saddle heights (Diefenthaeler, et al., 2006; Ericson, et al., 1985). However, there is some lack of information regarding the relationship between saddle height, saddle horizontal position and joint mechanical work.

*Table 4. Summary of the publications related to the effects of saddle height on joint mechanical work and coordinative pattern*

| Publication | Type | Subjects | Findings | Applied model |
|---|---|---|---|---|
| Nordeen Snyder (1977) | Original | Ten healthy subjects | Kinematic patterns showed no variation in the range of motion Korff, et al., at the hip, values at the dead centres did change. The major adaptations to increases in saddle height are found at the knee and in the ankle plantar flexor. | Partial kinematic (only joint angles) |
| Ericson, et al. (1985) | Original | Six healthy subjects | An increase of the saddle height increased the muscle activity in the *gluteus medius*, medial hamstring and *gastrocnemius medialis* muscles. | EMG |
| Ericson & Nisell (1987) | Original | Six healthy subjects | Patellofemoral compressive forces are reduced with the increase of saddle height | Kinetic |
| Horscroft, et al. (2003) | Original | Four well--trained cyclists | Cycling with a reduced saddle height did not elicit significant changes in joint power distribution. | Kinetic |
| Diefenthaeler, et al. (2006) | Original | Three well--trained cyclists | Pedaling technique, joint angles and muscle activation was affected by saddle height modifications | Pedal force, joint kinematics and EMG |

Despite the unchanged joint contribution (Horscroft, et al., 2003), several variables were reported to be affected by saddle height management, as previously summarized. Future studies should analyze the saddle height effects in joint moment distribution, joint kinematics and joint reaction forces simultaneously, as an attempt to improve on comprehension on the coordinative pattern during cycling.

## Perspective analysis for future research:

Throughout this review we have reported that different models have been applied to the measurement of mechanical work during cycling, even with differences in complexity and limitations. Most results regarding mechanical work during cycling have been based on a kinetic model, due to the possibility of comparing hip, knee, and ankle joint contribution to the mechanical work (Ericson, 1988; Hoshikawa, et al., 2007). Some evidence has been reported based on computational simulation models (Neptune, et al., 2000), which have been suggested to increase the reliability of the analysis regarding the pedaling movement due to the computation of co-contractions (Neptune, et al., 2000). Unfortunately, the application of computational simulation has been limited to steady-state cycling (Neptune, et al., 2000), which does not provide any further evidence to coordinative pattern. Future research should concern the application of the computational simulation model to the analysis of different workloads, pedaling cadence, saddle height effects, and others.

Some recent studies have reported that pedaling skills differ from training experience (Candotti, et al., in press; Chapman, et al., 2007), which suggests the application of a computational simulation model to compare cyclists, non-cyclists, and triathletes. Only Hoshikawa, et al. (2007) have indicated a different joint mechanical work distribution between cyclists and non-cyclists, but a lack of evidence regarding the individual muscle contribution still remains with the comparison of cycling experience and training level.

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# BIOMEHANIČKI RAD I KOORDINACIJSKA STRUKTURA VOŽNJE BICIKLA: PREGLED LITERATURE

## Sažetak

### Uvod

Bicikl je prijevozno sredstvo iznimno korišteno u cijelom svijetu. Kada je riječ o potrošnji energije tijekom vožnje biciklom, može se primijetiti da su mehaničke karakteristike (geometrija) bicikla unapređivane tijekom vremena kako bi se smanjila potrošnja energije, poboljšala brzina prijenosa i, očigledno, povećala ekonomičnost kretanja. Mehanički rad tijekom vožnje biciklom trebalo bi također analizirati u kontekstu poboljšanja ekonomičnosti kretanja, i to analizom koordinacijskog obrasca pokreta. Na taj način, optimizacija mišićne funkcije predstavljena je kao učinkovito rješenje za poboljšanje ravnoteže između mehaničkog rada i metaboličke energije. Mi još uvijek ne razumijemo potpuno kontrolu generiranja mišićne sile iz središnjeg živčanog sustava (koordinacijski obrazac pokreta), no ipak se dosta toga zna. U skladu s navedenim, u ovom radu pokušali smo ukratko predstaviti tri modela izračunavanja mehaničkog rada, koncept generiranja snage u mišićima zglobova koji sudjeluju u okretanju pedala tijekom vožnje standardnom brzinom te neke teorije koje se odnose na transfer energije kroz zglobne sustave i analizu koordinacijskog obrasca promatranjem distribucije mehaničkog rada u zglobovima. Naposljetku, izvijestili smo o učincima opterećenja, ritma okretanja pedala i visine sjedala na mehanički rad zglobova. Da bismo prikupili članke vezane uz glavni problem ovog preglednog članka obavljeno je kompjutersko pretraživanje najkorištenijih baza podataka ili agregatora baza (MEDLINE, SCOPUS, ISI Web of Knowledge, EBSCO i GOOGLE SCHOOLAR), kao i brojnih pojedinačnih časopisa dostupnih u papirnatom obliku. Ključne riječi za pretraživanje relevantnih članaka bile su: mišićni mehanički rad, koordinacijski obrazac, snaga mišića u zglobovima, visina sjedalice, opterećenje i ritam okretanja pedala.

**Modeli za izračunavanje mehaničkog rada:** Na temelju promjena kinetičkih i potencijalnih energija svakog segmenta (unutarnji rad), model koji je predstavio Fenn (1930a,b) prilagođavao se godinama. Elftman (1939) je predstavio drugačiji pristup za izračunavanje mehaničkog rada u zglobovima koji je koristio rezultante zglobnih momenata i kutne brzine za izračunavanje snage svakog zgloba (kinetički model). Kompleksniji model izračunavanja mehaničkog rada kod okretanja pedala predstavili su Neptune i Van Den Bogert (1998) koji su u kompjutersku simulaciju gibanja uključili 28 mišića i njihove karakteristike sile-dužine-brzine. Ovaj model bio je naveden kao najosjetljiviji za objašnjavanje mišićne koordinacije tijekom okretanja pedala na biciklu, ponajviše stoga što analizira i mišićnu ko-kontrakciju.

**Generiranje snage u mišićima zglobova koji sudjeluju u okretanju pedala tijekom vožnje standardnim ritmom:** Za razliku od hodanja i trčanja, kod okretanja papučica bicikla veći se dio mehaničke energije, povezane s cikličnim kretnjama, dobiva iz koncentričnih mišićnih akcija donjih ekstremiteta. Rezultati također pokazuju da se u pedaliranju skladišti elastična energija, istina, manja nego u trčanju.

**Transfer mehaničke energije kroz zglobne sustave i koordinacijski obrazac gibanja:** Biciklizam, kao višezglobni zatvoreni kinetički lanac, razvija silu i prenosi snagu kroz kukove, koljena i gležnjeve. Broker i Gregor (1994) proveli su analizu transfera energije koristeći kinetički model mehaničke energije. Fregly i Zajac (1996) stvorili su simulacijski model koristeći samo kinematičke podatke. Neptune, Kautz i Zajac (2000) također su stvorili simulacijski model za analizu najvažnijih mišićnih grupa povezanih s cikličnim gibanjem u biciklizmu. Rezultati njihovih istraživanja otkrili su nam da mišići zgloba stopala (m. soleus, m. gastrocnemius i m. tibialis anterior) imaju vrlo važnu funkciju u transferu mehaničke energije ekstremiteta na papučicu bicikla, dok se mišići kvadricepsa i m. gluteus maximus povezuju s proizvodnjom mehaničke energije. Bolje razumijevanje funkcioniranja mišićnih grupa u biciklizmu omogućilo je i kvalitetnije objašnjavanje koordinacijskog obrasca kretanja pri samom okretanju pedala.

**Učinci opterećenja na mehanički rad zglobova i koordinacijski obrazac kretanja:** Prvi rezultat, posljedica upravljanja opterećenjem, jest da dolazi do povećanja pozitivnog mehaničkog rada koji proizvode mišići zglobova uključenih u okretanje papučica bicikla, što je povezano s koncentričnom mišićnom kontrakcijom. Čini se da je doprinos mišića kukova i koljena promjenama opterećenja tijekom vožnje bicikla različit od doprinosa mišića zgloba stopala, budući da mišići zgloba stopala moraju biti prilagođeni za optimizaciju čvrstoće i maksimiziranja učinkovitosti transmisije mehaničke energije na pedalu bicikla.

**Učinak ritma okretanja papučica na mehanički rad zglobova i koordinacijski obrazac gibanja:** Također je analiziran učinak ritma okretanja pedala na mehanički rad zglobova radi objašnjenja koordinacijskog obrasca gibanja tijekom vožnje biciklom. Pri jednakom izlazu snage, povećani unutarnji rad s povećanjem ritma okretanja pedala povezan je s negativnom snagom ekscentrične kontrakcije mišića koja se proizvodila zbog pokušaja kontroliranja primjene sile na papučice. Izabran je najprihvatljiviji ritam okretanja pedala koji će odgovarati omjeru između proizvodnje sile i brzine skraćivanja mišića. Dok male promjene u ritmu okretanja pedala (od 90 do 100 o/min) ne utječu na distribuciju mehaničkog rada, čini se da velike promjene ritma okretanja pedala ili mijenjaju ili ne utječu na doprinos kuka, koljena i gležnja na ukupni mehanički rad. Autori su se jedino složili oko činjenice da se dopri-

nos mišića gležnja na ukupni mehanički rad ne mijenja s promjenama ritma okretanja pedala.

**Učinak visine sjedala na mehanički rad zglobova i koordinacijski obrazac kretanja:** Provedena su i istraživanja o upravljanju visinom sjedala bicikla radi utvrđivanja obrasca opterećenja zglobova pri različitim visinama, budući da je dokazano kako je većina ozljeda u biciklizmu povezana s lošim pozicioniranjem vozača na biciklu. Također je objavljen i podatak da distribucija snage zgloba nije pod utjecajem smanjenja visine sjedalice na biciklu. Nažalost, nije pronađeno nijedno istraživanje koje se bavilo ispitivanjem utjecaja visine sjedalice na distribuciju mehaničkog rada zglobova, a isto tako nisu pronađeni ni simulacijski modeli koji analiziraju generiranje mišićne sile pri različitim visinama sjedalice bicikla. Objavljeni su samo EMG podaci kojima su se pokušali objasniti i razumjeti koordinacijski obrasci kretanja tijekom vožnje bicikla na različitim visinama sjedalice.

**Prijedlozi budućih istraživanja:** U ovom preglednom članku predstavljeni su različiti modeli koji se primjenjuju za mjerenje mehaničkog rada u biciklizmu. Većina rezultata tih istraživanja bazirani su na kinetičkim modelima zbog toga što omogućuju usporedbu doprinosa zgloba kuka, koljena i gležnja ukupnom mehaničkom radu. Predstavljeni su i neki dokazi koji se temelje na proračunskim simulacijskim modelima, a koji predlažu povećanje pouzdanosti analize gibanja u biciklizmu pomoću procjene ko-kontrakcije mišića. Buduća istraživanja trebala bi se orijentirati na upotrebu računalnih simulacijskih modela za analizu različitih opterećenja vožnje bicikla, ritma okretanja pedala, utjecaja visine sjedalice i sličnih znanstvenih problema.