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LOAD MOMENTS ABOUT THE HIP AND KNEE JOINTS DURING ERGOMETER CYCLING

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ABSTRACT. The aim of the study was to calculate the magnitudes of moments of force acting about the bilateral hip and knee joint axes during ergometer cycling. Six healthy subjects pedalled a weight-braked bicycle ergometer at different workloads, pedalling rates, saddle heights and pedal foot position. During cycling at 120 Watts, 60 revolutions per minute with mid-saddle height and anterior pedal foot position, the mean peak flexing and extending hip load moments were 34.3 and 8.9 Nm, respectively. Mean peak flexing knee load moment was 28.8 Nm and extending moment was 11.9 Nm. Hip load moments were significantly increased by increasing the ergometer workload or pedalling rate. For knee load moments, workload was the most important factor. The flexing knee load moment did not change with changes in pedalling rate. Different saddle heights or pedal foot positions had a slight but not always statistically significant influence on the hip and knee joint loads. The maximum hip and knee joint load moments induced during cycling were small compared with those obtained during other exercises or normal activities such as level walking, stair climbing, and lifting.

Key words: biomechanics, joint load, physical therapy exercise, rehabilitation

In the rehabilitation of patients with fragile joint components, a balance may be sought between the lowest possible load on these and the need for efficacious training, e. g. high leg muscular activity or cardiovascular load. Patients with load-elicited pain should be able, with appropriate adjustment of the ergometer cycling, to achieve a minimum of load on injured or fragile lower limb joint components. This would then help them to maintain adequate exercise load, yet avoid any pain increase or benefit from a reduction of, or relief from, pain. Biomechanical studies on hip and knee joint moments induced during exercise on a bicycle ergometer may be useful in the individual optimization of cycling exercise and for comparing ergometer cycling with other therapeutic exercises (19, 25), or with everyday activities such as level walking (2, 17), stair climbing (1) or lifting (5, 18).

The bicycle ergometer has been used as an exercise apparatus in postoperative care after hip (26), knee (4, 12) and ankle joint (10, 15) surgery, and in the rehabilitation of patients with rheumatoid arthritis (24), or various kinds of knee dysfunction (13, 14, 16).

Several studies of joint load during cycling have been presented recently (6, 8, 10, 12, 27). Van Elegem et al. (27) performed a vector analysis of knee joint forces about the bilateral knee joint axis (about which flexion and extension motions occur) during cycling racing. They estimated a compressive knee joint force of 75 kg (corresponding to 736 N) for a person weighing 60 kg. Henning et al. (12) performed an in vivo strain gauge study of elongation of the anterior cruciate ligament during different activities. They found that cycling produced only 7% of the elongation occurring in an 80 pound (365 N) Lachman test, and proposed that the proper order for a rehabilitation program should be crutch walking, cycling, walking, slow running, and faster running. Ericson et al. (6) determined the knee joint load moment about the anterio-posterior knee joint axis (about which varus and valgus moments occur) during exercise on a bicycle ergometer and found that the load was about the same as induced during level walking. In another study (8), the dorsiflexing load moment about the bilateral axis of the talocrural joint was reported to be 30.9 Nm. Recently Gregor et al. (9) reported on the hip, knee and ankle joint moments induced during cycling. They found that there was an extending knee load moment (knee flexor moment) starting approximately halfway through the propulsive phase of crank rotation (0-180 degrees). The knee flexor moments were presented as a creative solution to Lombard's paradox (the activity of a two-joint muscle when the required moment at one of the joints is in the opposite direction to that caused by the muscle). McLeod & Blackburn (16) used another approach

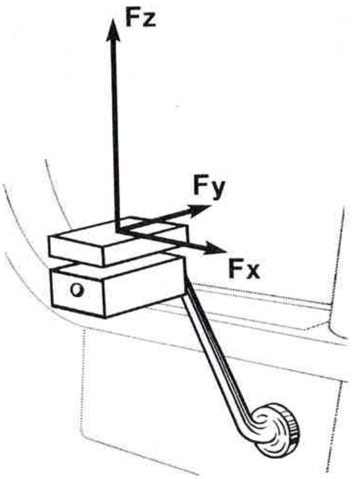

Fig. 1. The specially instrumented force measuring pedal and the direction of the three different pedal reaction forces *Fx*, *Fy* and *Fz*.

in a kinematic study where they studied the variation of the inclination of the tibial plateau during cycling and its possible consequences for the knee load. However, neither forces nor loading moments were calculated. The widespread use of cycling in medical rehabilitation supports further biomechanical investigations of cycling as exercise.

The general purpose of the present investigation was to study how hip and knee load moments were affected by changes in ergometer workload, pedalling rate, saddle height and the position of the foot on the pedal.

The following specific questions were analysed:

1. What is the magnitude of the load moment about the bilateral hip and knee joint axes during standardized ergometer cycling?

2. How do the maximum hip and knee load moments vary with workload, pedalling rate, saddle height, and position of the foot on the pedal?

MATERIALS AND METHODS

Six healthy subjects (who gave informed consent) all men aged between 20 and 31 years (mean=25.3 years) participated in the study. Their average height and weight were 1.80 m (SD=0.06) and 71.3 kg (SD=5.0). The subjects were students with ordinary daily and recreational cycling experience. None of the subjects suffered from locomotor pain, had previously undergone any joint surgery, or had had any periods of sick leave due to disorders of the musculoskeletal system.

A bicycle ergometer (Cardionics with weight brakes, Cardionics, Stockholm, Sweden) with a specially-instrumented pedal (see below) was used. The following variables were studied:

1) *workload*: zero, 120 and 240 Watt (W)

2) *pedalling rate:* 40, 60, 80 and 100 revolutions per minute (rmp)

3) *saddle height:*'low, mid, and high' determined as a percentage (102, 113, 120%) of the distance between the ischial tuberosity and the medial malleolus measured on each subject. The saddle height was measured as the greatest distance from saddle surface to the centre of the upper pedal surface in a straight line along saddle pillar and crank.

4) *foot position:* one anterior foot position and one posterior foot position were used. The anterior was defined as the position when the centre of the pedal was in contact with the head of metatarsus II (ball of foot), and the posterior foot position approximately 10 cm backward (instep).

The different test combinations studied are shown in Table I. The reasons for choosing these bicycle parameters are discussed elsewhere (8). In the present study combination numbers 8 and 10 were excluded from the biomechanical analysis. Cycling in the highest saddle position and using the posterior (instep) foot position (comb. 10) gave an unnatural cycling position with tendencies to pelvis rocking and hip motion in the frontal plane.

When one of the four variables was changed and studied, the other three were held constant. The one major exception was that the pedalling rate was changed (40, 60, 80 and 100 rpm) a braking weight of 2 kg was used and hence the workload was 80, 120, 160 and 200 W, respectively. The different workload were regulated by adding weights (zero, 2 and 4 kg) to the weight braked bicycle ergometer. 120 W, 60 rpm, mid-saddle and anterior foot position were chosen as constant variables. This combination will be referred to as 'standardized ergometer cycling' (comb. 2). In order to eliminate systemic effects of fatigue, the internal sequence of the eleven different test

Table I. *Summary of the different combinations of the parameters studied*

No:	Workload (W)	Pedalling rate (rpm)	Saddle height	Foot position
1	0	60	Mid	Anterior
2[a]	120	60	Mid	Anterior
3	240	60	Mid	Anterior
4	80	40	Mid	Anterior
5	160	80	Mid	Anterior
6	200	100	Mid	Anterior
7	120	60	Low	Anterior
8	120	60	Low	Posterior
9	120	60	Mid	Posterior
10	120	60	High	Posterior
11	120	60	High	Anterior

[a] Combination no. 2 is referred to in the text as 'standardized ergometer cycling'.

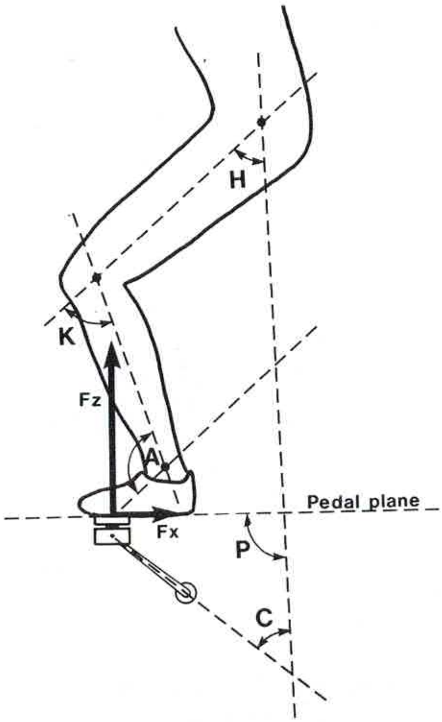

Fig. 2. Positions of the bilateral hip (*H*), knee (*K*) and ankle (*A*) joint axes, pedal plane (*P*) and crank (*C*) angle.

situations was randomized. The saddle heights determined as described above were adjusted to the nearest fixed position with a maximum error of ±1.5 cm. The handlebars were kept level with the saddle. The cyclist's trunk was inclined forward 20–30° from the vertical. All subjects were allowed to warm up and familiarize themselves with cycling on the specially instrumented bicycle ergometer. They practised at all the different workloads, pedalling rates, saddle heights and foot positions included in the study.

All measurements were performed on the left lower limb. In the left pedal, a quartz force transducer (Kistler type 9251 A) was mounted. The equipment allowed forces in the three orthogonal dimensions (*x*, *y* and *z*) to be measured (Fig. 1). In the present study the forces acting in the sagittal plane *Fx* and *Fz* was used for calculation of the moments of force acting about the bilateral hip and knee joint axes. The forces were recorded on a UV-recorder (Honeywell 1508 Visicorder). A switch was mounted on the bicycle ergometer for marking on the UV-recorder the top position of the crank for each revolution. Time was registered on the UV-recorder parallel to force and crank top position using a specially designed time indication panel with a light-emitting diode display giving a bar representation of time in units down to 1 msec. The different test situations were filmed using a 16 mm cine-film camera (Paillard Bolex, 60 frames/sec), mounted perpendicular to the sagittal plane of the subject at a distance of 3.5 m. As landmarks for the bilateral hip, knee and ankle joint axes, dye marks were placed on the skin at approximately 1 cm anterior and superior to the tip of the great tubercle of femur, at the centre of the lateral femoral epicondyle and at the tip of the lateral malleolus. Time as indicated by the time indication panel was visible on each film frame.

The subjects cycled for approximately 30 sec on each test occasion before the measurements were taken. A metronome was used to enable each subject to find and keep the correct pedalling rate. The subjects were filmed and the forces registered for 5 sec. One of the approximately five revolutions registered on the UV-recorder was selected and analysed throughout the complete pedal revolution. The film was analysed using an Analector ANL4 projector, which made it possible to 'freeze' the film and trace the picture at intervals of approximately 15 degrees crank angle. This method for registration of lower limb kinematics has been described and used earlier (19, 25). The position for the hip, knee and ankle joint axes, the pedal plane and the crank angle were then determined using the traced pictures (Fig. 2). The *Fz* and *Fx* force values corresponding to each picture were read from the UV-recorder.

The model used in the present study for calculating hip

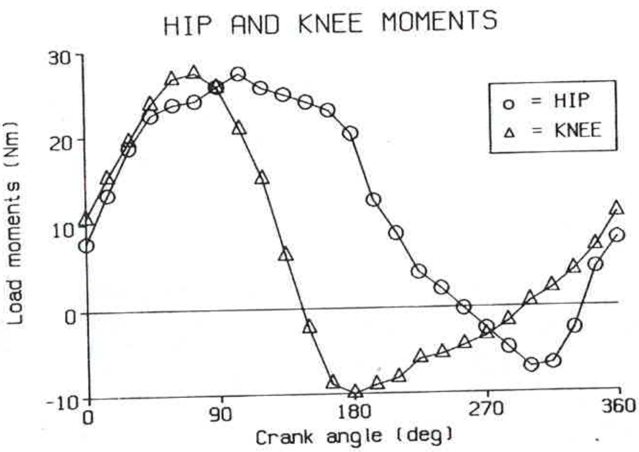

Fig. 3. Load moment acting about the bilateral hip and knee joint axes during standardized ergometer cycling (120 W, 60 rpm, mid saddle height and anterior foot position, combination number 2).

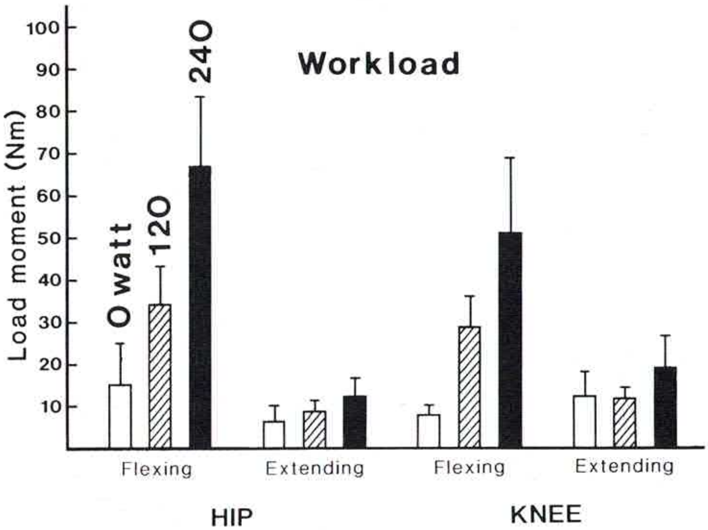

Fig. 4. Mean peak hip and knee joint load moments induced during cycling with three different workloads; 0, 120 and 240 W.

and knee load moments has been described in detail elsewhere (3). It is based upon dynamic mechanics and takes into account the dynamically-induced forces and moments due to forces of inertia and translational motions of the lower limb. With the crank angle, pedal plane angle, joint positions and pedal reaction forces known, the limb motions and joint load moments were calculated.

The significance of changes in hip and knee load moments due to changes of workload, pedalling rate, saddle height and foot position was statistically treated and analysed with ANOVA. The level of significance was $p<0.05$ troughout.

RESULTS

The mean load moments acting about the bilateral hip and knee joint axes during 'standardized' ergometer cycling (120 W, 60 rpm, mid saddle height and anterior foot position) are shown in Fig. 3. Zero and 360° of crank angle correspond to the top position of the pedal and 180° crank angle corresponds to the bottom position. The hip load moment was predominantly flexing, except for the period between approximately 255° and 335° crank angle, where it was extending. The mean peak flexing and extending hip load moments were 34.3 Nm (SD=9.1) and 8.9 Nm (SD=2.6), respectively. The knee load moment was flexing between approximately 300° and 140° crank angle. For the rest of the motion cycle, (140–300° crank angle) the knee load moment was extending. Mean peak knee flexing

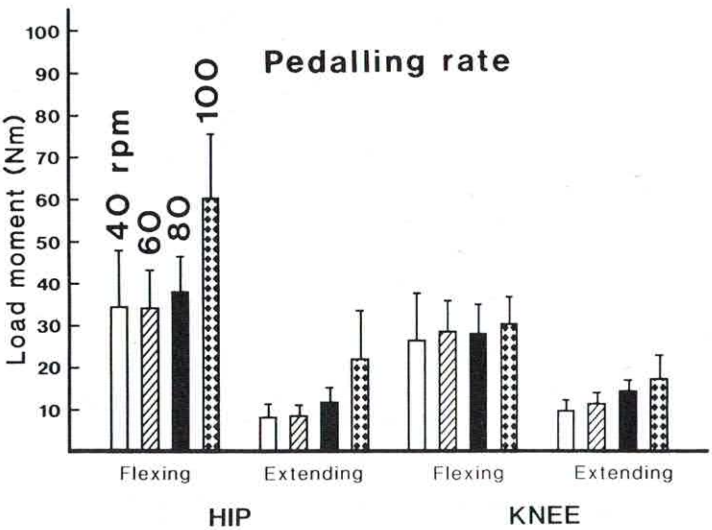

Fig. 5. Mean peak hip and knee joint load moments induced during cycling at four different pedalling rates; 40, 60, 80 and 100 rpm.

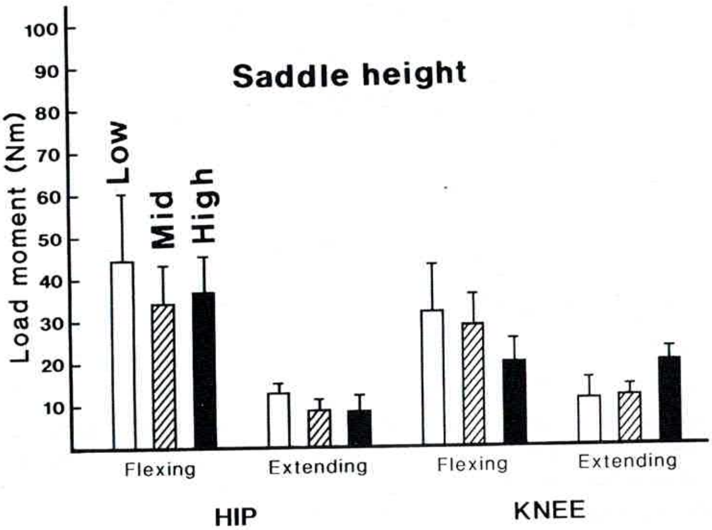

Fig. 6. Mean peak hip and knee joint moments induced during cycling with three different saddle heights; 'low, mid, and high'.

and extending load moment were 28.8 Nm (SD=7.5) and 11.9 Nm (SD=2.6), respectively.

The mean peak hip and knee load moments induced at different workloads are shown in Fig. 4. The maximum extending are flexing hip and knee load moments increased with an increase in ergometer workload. The magnitude of the increase tended to be more pronounced for the flexing load moments than for the extending load moments about both the hip and the knee joints.

The mean peak hip and knee load moments induced at different pedalling rates are shown in Fig. 5. An increase in pedalling rate increased the maximum flexing hip load moment and the maximum extending load moments at the hip and knee joints. The maximum flexing knee load moment was not increased with an increased pedalling rate.

The mean peak load moments acting about the hip and knee during cycling at different saddle heights are shown in Fig. 6. Increased saddle height did not significantly alter the maximum flexing hip load moment, but decreased the extending hip load moment. The maximum flexing knee load moment was decreased and the maximum extending knee load moment increased with increased saddle height.

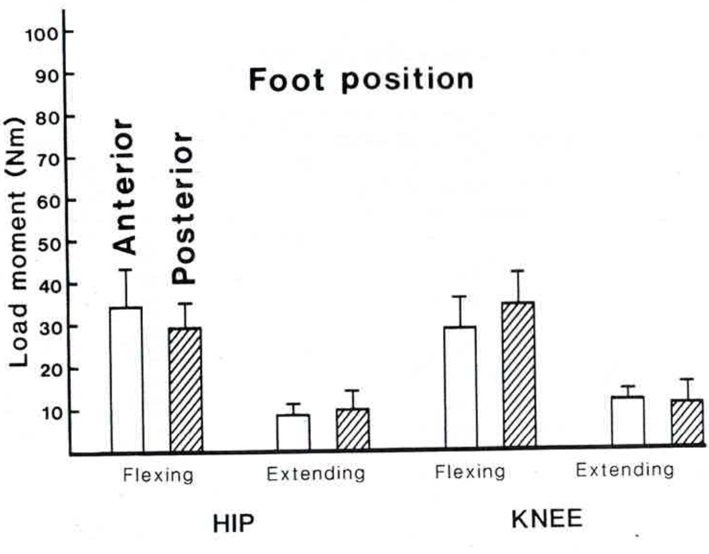

Fig. 7. Mean peak hip and knee joint load moments induced during cycling with two different pedal foot positions; 'anterior' (ball of foot) or 'posterior' (instep).

Table II. *Changes in maximum hip and knee load moments at various adjustments during ergometer cycling, and their statistical significances ($p<0.05$)*

Adjustment factor	Flexing hip load moment	Extending hip load moment	Flexing knee load moment	Extending knee load moment
Increased workload	+	+	+	+
Increased pedalling rate	+	+	*ns*	+
Increased saddle height	*ns*	–	–	+
Posterior foot position instead of anterior	*ns*	*ns*	*ns*	*ns*

+=increased load moment, *ns*=no significant change in load moment
–=decreased load moment

The mean peak hip and knee load moments induced with different pedal foot positions are shown in Fig. 7. The use of the posterior foot position instead of the anterior did not significantly alter the hip and knee load moments.

A summary of the changes in hip and knee load moments obtained during alterations of the parameters studied is given in Table II.

DISCUSSION

The method used for estimating the hip and knee load moments induced during cycling was based upon measurement of the forces applied to the pedal, on cine-film recordings of lower limb kinematics and on a dynamic mechanical calculation model.

In an earlier study (3) we showed that the pedal plane angle (P) (Fig. 2) was a very sensitive error factor in calculation of the magnitude of hip and knee load moments. An error in measuring or recording the pedal plane angle would cause an error in the direction of the resultant pedal reaction force. This in turn would introduce errors in the mechanical calculation. We determined a maximum test–retest error of ±1° for the pedal plane angle that introducing errors of up to 7.5 and 8.6% in the calculation of the peak hip and knee load moments respectively. The temporal patterns and magnitude of hip and knee moments were in general agreement with those recently reported by Gregor et al. (9). Our calculation model includes all dynamic mechanical components such as forces of inertia, which are important when calculating joint moments during fast motions such as cycling.

It might be useful to compare the hip and knee load moments obtained during ergometer cycling with the load induced during other therapeutic exercises or common activities (Table III). The maximum flexing hip load moment (balanced by the hip extensors) induced during ergometer cycling was somewhat higher than during slow jogging (28) but

Table III. *Summary of reported peak hip and knee load moments about the bilateral hip and knee joint axes during various activities*

Authors	Activity	Max. flexing hip load moment (Nm)	Max. extending hip load moment (Nm)	Max. flexing knee load moment (Nm)	Max. extending knee load moment (Nm)
Morisson (17)	Level walking	–	–	35	28
Boccardi et al. (2)	Level walking	100	30	50	40
Winter (28)	Slow jogging	25	18	53	13
Andriacchi et al. (1)	Climbing stairs	124	–	54	48
Andriacchi et al. (1)	Going down stairs	112	–	147	43
Németh et al. (18)	Lifting 13 kg	124	–	–	–
Ekholm et al. (5)	Lifting 13 kg	–	–	50	55
Németh et al. (19)	Rising exercises	45	–	–	–
Schüldt et al. (25)	Rising exercices	–	–	62	25
Ericson et al. (present study)	Ergometer cycling	34.3	8.9	28.8	11.9

lower than in level walking (2, 17), stair climbing (1), rising exercise with back supported (19, 25) or lifting (5, 18). For rehabilitation of patients with coxarthrosis, for example, and tendency to load induced pain, a possible sequence of exercise might thus be to use cycling before normal level walking and stair walking are tried. The extending hip load moment (balanced by hip flexors) during cycling was even lower than the low load obtained during level walking and slow jogging. The maximum flexing and extending knee load moments induced during 'standardized' ergometer cycling were lower than the maximum knee moments obtained during the other activities reported in Table III. For knee patients (e. g. gonarthrosis or reumatoid arthritis) cycling can be used early in the rehabilitation process.

When adjusting the bicycle ergometer, or the cycling technique used, in order to change the load moment on a certain joint, the load on another joint may also be changed. This must be considered, particularly when the patient has disorders or pain in more than one joint. Changes in saddle height or pedal foot position alter the geometry of the closed 4-bar linkage (crank, foot, shank and thigh), which alters important physiological and mechanical factors such as muscle length, joint range of motion and moment arms of external forces and muscle forces. Hence, adjustments made to ergometer or technique are important for joint load moments, muscular activity and energy expenditure during cycling. Changes in oxygen consumption (11, 23) and in muscular activity (7) due to changes in saddle height have been described elsewhere.

The hip and knee load moments reported in the present study could, together with calculation of internal forces be further analysed with local biomechanical models to establish, the compressive forces in the hip (20) and knee (21, 22) joints. Such analyses are in progress and ought to extend the possibilities of evaluating the use of ergometer cycling as exercise for different patients with hip and knee joint disorders.

The present study aimed at estimating the magnitude of hip and knee load moments and how these loads can be altered by different adjustment factors. Such information should be clinically valuable when designing rehabilitation programmes for patients' differing needs.

The following summary may provide some guide for clinical practice:

1) The hip and knee load moments induced during ergometer cycling are low compared with those induced in most other activities. For instance, normal ergometer cycling induces hip extensor load which is about one-third of that in level walking and stair climbing. The load on the knee extensors in ergometer cycling is about half that in stair climbing and one-fifth of that when going downstairs.

2) An increase in ergometer workload increased the hip and knee load moments more than did the other adjustment factors studied. For instance; an increase from zero to 120 W and from 120 to 240 W each approximately doubled the flexing hip and knee loads.

3) There were small changes in hip and knee load moment when cycling at different pedalling rates (40, 60 and 80 rpm), except for the highest pedalling rate studied, 100 rpm, which significantly increased the flexing hip load moment.

4) Increasing the saddle height reduced the flexing knee load moment by one-third.

5) Change in foot position did not alter the hip and knee load moments.

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