Patellofemoral Joint Forces During Ergometric Cycling

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We estimated the patellofemoral joint forces generated during pedaling on a bicycle ergometer. Our calculations were based on measurements from a force transducer mounted on the pedal, 16-mm cine-film sequences, and biomechanical models of the cycling motion and of the patellofemoral joint. Six healthy male subjects cycled at different work loads, pedaling rates, saddle heights, and pedal foot positions. The maximum patellofemoral compressive force was 905 N (1.3 times body weight [BW]) when cycling with an anterior foot position at 120 W, 60 rpm, and middle saddle height. The mean peak compressive force between the quadriceps tendon and the intercondylar groove was 295 N (0.4 BW), and the patellar-tendon and quadriceps-tendon strain forces were 661 N (0.9 BW) and 938 N (1.3 BW), respectively. The patellofemoral joint forces were increased with increased work load or decreased saddle height. Different pedaling rates or foot positions did not significantly change these forces.

Key Words: Biomechanics, Exercise therapy, Knee, Patella.

Pedaling on a bicycle ergometer is one possible treatment of patients with patellofemoral disorders¹⁻⁵ or rheumatoid arthritis.⁶ Knowledge of the magnitude of the patellofemoral joint forces generated during bicycling may be valuable to physical therapists who treat patients with load-elicited pain from the patellofemoral joint. Patients, by appropriately adjusting the bicycle ergometer and their own cycling technique, may achieve a decrease in patellofemoral joint forces that still would give them adequate quadriceps-tendon exercise while reducing pain.

The moments of force acting about the knee joint during exercise on a bicycle ergometer have been reported recently.^{7,8} In these studies, a force-measuring pedal was used. If the reaction forces applied to the foot from the pedal are known, the moments of force acting about the bilateral hip, knee, and ankle joint axes can be calculated using dynamic mechanics.⁹

During standardized ergometric cycling, defined as 120 W, 60 rpm, middle saddle height, and anterior foot position, the mean peak knee flexion and extension load moments (counteracted by a muscular moment) acting about the bilateral knee joint axis are about 29 N·m and 12 N·m, respectively.⁸ The knee load moments acting about the anteroposterior knee joint axis are about 25 N·m in a varus direction and 3 N·m in a valgus direction.⁷ The tibiofemoral peak compressive force and the anteriorly directed peak shear force mainly stressing the anterior cruciate ligament recently were estimated to be about 1.2 and 0.05 times body weight (BW), respectively.¹⁰

Nisell and Ekholm constructed a biomechanical model for estimating the magnitude of patellofemoral compressive forces, patellar-tendon and quadriceps-tendon strain forces, and compressive forces between the quadriceps tendon and the femoral intercondylar groove.¹¹ Their study showed that with a constant knee flexion load moment (counteracted by knee extension), the patellofemoral compressive force increases with an increased knee flexion angle. At knee flexion angles greater than 90 degrees, however, the patellofemoral compressive force diminishes slightly. The magnitude of the knee flexion load moment and the degree of knee joint flexion present are the decisive factors for the patellofemoral joint force magnitudes during various activities. In ergometric cycling, the maximum knee flexion load moment is significantly increased by a work-load increase or by a saddle height decrease.⁸ Different pedaling rates or foot positions do not significantly affect the magnitude of the maximum knee flexion load moment.⁸

In this study, we used the data presented on knee load moments during ergometric cycling⁸ and a biomechanical model for patellofemoral joint forces¹¹ to calculate the patellofemoral joint forces induced. The purpose of our study was to quantify the magnitude of patellofemoral compressive forces obtained during ergometric cycling. We estimated the compressive forces between the quadriceps tendon and the intercondylar groove and the strain forces in the patellar and quadriceps tendons achieved during cycling. Changes in these forces caused by changes in ergometric work load, pedaling rate, saddle height, or pedal foot position also were studied.

METHOD

Subjects

The subjects were six healthy men aged 20 to 31 years, ($\overline{X} = 25.3$ years), who gave their informed consent to participate in the study. Their average height and weight were 1.8 m (s = .06) and 71.3 kg (s = 5.0). The subjects were students with ordinary daily and recreational cycling experience. None of the subjects suffered from locomotor pain, previously had undergone joint surgery, or had a history of musculoskeletal disorders.

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This article was submitted March 10, 1986; was with the authors for revision 27 weeks; and was accepted January 21, 1987. Potential Conflict of Interest: 3.

Procedure

We used a bicycle ergometer* with weight brakes and a specially instrumented pedal to study the following variables:

- 1. Work load: 0, 120, and 240 W.
- 2. Pedaling rate: 40, 60, 80, and 100 rpm.
- 3. Saddle height: low, mid, and high, determined as a percentage (102%, 113%, and 120%, respectively) of the distance between the ischial tuberosity and the medial malleolus as measured on each subject. The saddle height was measured as the greatest distance from saddle surface to the center of the upper pedal surface in a straight line along the saddle pillar and crank.
- 4. Foot position: one anterior and one posterior foot position. The anterior foot position occurred when the center of the pedal was in contact with the head of the second metatarsus (ball of the foot), and the posterior foot position occurred about 10 cm backward (instep).

Table 1 shows the different test combinations studied. We chose to exclude combinations 8 and 10 from the biomechanical analysis. Cycling in the highest saddle position and using the posterior foot position (combination 10) gave an unnatural cycling position with tendencies to have pelvic rocking and hip motion in the frontal plane. To eliminate systemic effects of fatigue, we randomized the internal sequence of the 11 different test situations.

When one of the four variables was changed and studied, the other three were held constant. The only exception was that when the pedaling rate was changed (40, 60, 80, and 100 rpm), a braking weight of 2 kg was used and hence the work loads were 80, 120, 160, and 200 W, respectively. The different work loads were regulated by adding weights (0, 2, and 4 kg) to the weight-braked bicycle ergometer. We chose 120 W, 60 rpm, middle saddle height, and anterior foot position as the constant variables, which is the combination referred to as standardized ergometric cycling. The various saddle heights were adjusted to the nearest fixed position with a maximum error of \pm 1.5 cm. The handlebars were kept level with the saddle. The cyclist's trunk was inclined forward 20 to 30 degrees from the vertical position. All subjects were allowed to warm up and familiarize themselves with cycling on the specially instrumented bicycle ergometer. They practiced at all of the different work loads, pedaling rates, saddle heights, and foot positions included in the study.

All measurements were taken on the left lower limb. A piezoelectric quartz force transducer[†] was mounted in the left pedal. The equipment allowed us to measure forces in the three orthogonal dimensions (x, y, and z). We used the x and z forces in the sagittal plane to calculate the moments of force about the bilateral knee joint axis. The forces were recorded on a UV recorder.[‡] We mounted a switch on the bicycle ergometer for marking on the UV recorder the top position of the crank for each revolution. 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, we could record time on the UV recorder parallel to the force

TABLE	1					
Summai	ry of	Combinations	of	Ergometric	Cycling	Tests

Test	Work Load (W)	Pedaling Rate (rpm)	Saddle Height	Foot Position
1ª	0	60	mid	anterior
2	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	anterior
11	120	60	high	posterior

* Combination 2 is defined as standardized ergometric cycling.

and crank top positions. The different test situations were filmed using a 16-mm cine-film camera[§] that shot 60 frames a second, mounted perpendicular to the sagittal plane of the subject at a distance of 3.5 m. To identify landmarks for the bilateral hip, knee, and ankle joint axes, we placed dye marks on the skin at about 1 cm anterior and superior to the tip of the great tubercle of the femur, at the center 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 about 30 seconds during each test before we took the measurements. A metronome enabled each subject to find and maintain the correct pedaling rate. We filmed the subjects and recorded the forces during fivesecond intervals. One of the approximately five revolutions recorded on the UV recorder was selected and analyzed throughout the complete pedal revolution. We analyzed the film with an Analector ANL4 projector,¹ which allowed us to freeze the film and trace the picture at approximately 15degree intervals of the crank angle. The positions of the hip, knee, and ankle joint axes were determined using the traced pictures. The pedal and joint angles were measured from the cine-film. The x and z force values corresponding to each picture were read from the UV recorder.

The model used in this study for calculating knee load moments was based on dynamic mechanics, which took into account the dynamically induced forces and moments caused by forces of inertia and translational motions of the lower limb.⁹ The knee load moments had been calculated previously from known crank angles, pedal plane angles, joint positions, and pedal reaction forces.⁸

Patellofemoral Joint Force Analysis

Biomechanical models of the patellofemoral joint, based on anatomical data and mechanical principles, have been presented and explained in detail elsewhere.¹¹ Using this patellofemoral joint model (Fig. 1), the patellofemoral joint forces can be quantified if the knee flexion load moment (Mk) and knee flexion angle are known. The patellar moment arm

^{*} Cardionics AB, Frösätrabacken 24, S-127 37, Skärholmen, Sweden.

[†] Model 9251-A, Kistler Instrument Corp, 75 John Glenn Dr, Amherst, NY

^{14120.} ‡ Model 1508 Visicorder, Honeywell Inc, Medical Electronics Div, 1 Campus Dr, Pleasantville, NY 10570.

[§] Bolex, Div of Paillard, Inc, 1900 Lower Rd, Linden, NJ 07036.

 $[\]parallel$ Oud Delft, Div of Foreign Advisory Service Corp, Rte 1, Princess Anne, MD 21853.



Fig. 1. Free-body diagram of patella and distal part of the quadriceps tendon. Patellofemoral compressive force (Fcp) equals vector sum of patellar-tendon strain force (Fp) and quadriceps-tendon strain force (Fq). The Fcp, which is perpendicular to the joint surface, projects through the Fp-Fq intersection point (X) and the center of patellofemoral joint contact point (M). The patellar moment arm (dp) and compressive force between quadriceps tendon and femoral intercondylar groove (Fcq) are shown also. (Adapted from Nisell.¹²)

is denoted dp. The magnitude of the patellofemoral compressive force (Fcp), the patellar-tendon strain force (Fp), the quadriceps-tendon strain force (Fq), and the compressive force between the quadriceps tendon and the femoral intercondylar groove (Fcq) may be determined by the following equations:

$$Fp = Mk/dp$$
(1)

$$Fcp = Fp (\sin \Psi) / (\sin \epsilon)$$
 (2)

$$Fq = Fcp (\cos \epsilon) + Fp (\cos \Psi)$$
(3)

$$Fcq = 2 Fq (sin \lambda/2)$$
(4)

Data Analysis

The significance of changes in patellofemoral joint forces caused by changes in work load, pedaling rate, saddle height, and foot position was determined statistically using a onefactor analysis of variance (ANOVA) for repeated measures. The level of significance was set at .05.

RESULTS

The knee load moment, knee angles, Fcp, Fp, Fq, and Fcq calculated during standardized ergometric cycling are shown in Figure 2. Zero- and 360-degree crank angles correspond to the pedal top position, and the 180-degree crank angle corresponds to the pedal bottom position. The Fcp, Fp, and Fq peaked at the 60-degree crank angle (ie, during the downstroke before the crank became horizontal). The Fcq occurred between the 315- and 120-degree crank angles and peaked at the 30-degree crank angle. Figure 3 shows patellofemoral joint forces in relation to knee angle. The mean peak Fcp during standardized ergometric cycling measured 905 N (s = 240) and occurred at a mean knee angle of 83 degrees (s = 6). At the same knee angle, the peak Fp and Fq also were present, measuring 661 N (s = 175) and 938 N (s = 249), respectively. The mean peak Fcq measured 295 N (s = 70) at a mean knee angle of 108 degrees (s = 7).



Fig. 2. Knee load moment, knee joint angles, patellar-tendon strain force (Fp), quadriceps-tendon strain force (Fq), patellofemoral compressive force (Fcp), and compressive force between quadriceps tendon and femoral intercondylar groove (Fcq) induced during complete crank revolution.



Fig. 3. Patellar-tendon strain force (Fp), quadriceps-tendon strain force (Fq), patellofemoral compressive force (Fcp), and compressive force between quadriceps tendon and femoral intercondylar groove (Fcq) plotted against knee joint angle.

Figure 4 shows the changes in patellofemoral joint force magnitudes caused by changes of the different adjustment factors. The magnitude of the compressive and strain forces increased significantly with an increased work load or decreased saddle height. These forces were not changed significantly by a change in pedaling rate or pedal foot position (Tab. 2).

DISCUSSION

In our study, the peak Fcp induced during standardized ergometric cycling was calculated to be 905 N (1.3 BW), which may be similar to compressive forces obtained during other activities. Nisell estimated the patellofemoral joint forces during various activities using knee moment and knee joint angle data reported by others.¹² The maximum Fcp induced during standardized ergometric cycling is similar to that induced during normal level walking.^{13,14} The Fcp produced during cycling is about 50% of that produced when ascending stairs.¹⁵ During maximum isokinetic knee extension at 30°/



Fig. 4. Changes in patellar-tendon strain force (Fp), quadriceps-tendon strain force (Fq), patellofemoral compressive force (Fcp), and compressive force between quadriceps tendon and femoral intercondylar groove (Fcq) caused by changes of ergometer work load, pedaling rate, saddle height, or pedal foot position.

sec, the Fcp is about 10 times that induced during cycling.¹⁶ One must consider that the magnitude of the Fcp induced during cycling depends almost entirely on the ergometric work load or saddle height used, not on the subject's body weight. The Fcp expressed as BW, therefore, will be relatively smaller for heavier subjects.

Our results show that the compressive forces (Fcp and Fcq) obtained during cycling could be decreased even more by a reduction in work load or an increase in saddle height. The magnitude of Fcp induced during cycling is governed by the magnitude of knee load moment and the knee joint angle. When the saddle height was decreased, the knee load moment increased significantly, and the knee joint angle increased.⁸ Consequently, the patellofemoral joint forces induced at lower saddle heights increased.

The clinical experience is that some people complain about anterior knee joint pain induced during cycling.¹⁷ The cause of this pain is unclear. The compressive forces are similar to, or somewhat higher than, those produced during normal level walking, but lower than those produced during most other activities. The main difference between cycling and walking is that the knee is much more flexed during cycling. Fairbank et al proposed that anterior knee joint pain is caused by overuse, such as repetitive loading.¹⁸ Nisell and Ekholm earlier stated that patients with load-elicited pain from the patellofemoral joint might be advised to avoid knee angles above 30 degrees under loaded conditions.¹¹ As recently discussed by Nisell, however, the magnitude of the patellofemoral contact area varies with knee joint angle.12 The largest contact area is reported at 60 to 90 degrees of knee flexion, and the smallest contact area occurs when the knee is straight.^{19,20} Consequently, the patellofemoral pressure, even when the knee is almost straight, may be considerable, although the compressive forces seem to be comparatively low. In cycling, the knee is flexed more than 30 degrees during most of the revolution of the crank. Dickson stated that many bicycle riders make two major errors; they either set the saddle too low or set the gears too high.¹⁷ To avoid development of anterior knee pain, therefore, saddle height must be adjusted properly and the work load should not be too high.

The Fcq occurred at large knee flexion angles with a peak of 295 N at the 108-degree knee angle. This Fcq has been discussed in the literature and might lead to compression of the upper part of the suprapatellar bursa, in some cases even causing pain.²⁰⁻²³ We only can speculate about the etiological factors influencing anterior knee pain induced for some people during cycling, but factors such as increased knee flexion and compression of the suprapatellar bursa and the patellofemoral joint certainly are of considerable importance.

Lindberg relied heavily on the use of the bicycle ergometer in the treatment of patients with patellofemoral pain syndrome.³ He stated that a bicycle ergometer enables physical training with loads ranging from light to heavy. Using minimum resistance, a situation is created that replicates passive movement of the knee joint. As soon as possible, Lindberg's patients were put on the bicycle ergometer, using minimum or no load, and the resistance was increased gradually. The bicycle exercise was used both for improving joint mobility and muscle strengthening.³ Based on the results of our study and the clinical use of cycling reported elsewhere, we believe that cycling may be a valuable exercise in the treatment of patients with patellofemoral pain syndrome. Proper attention, however, must be given to the appropriate adjustment of work load and saddle height. TABLE 2

Mean Patellofemoral Compressive and Strain Forces During Ergometric Cycling at Different Adjustments (in Newtons)

A di vata anta	Fcp*		Fcq ^ø		Fp°		Fq ^d	
Adjustments	X	S	x	S	X	S	X	S
Work load (W)								
0	242	68	138	54	183	53	252	73
120	905	241	295	70	661	175	938	249
240	1,674	577	607	231	1,203	413	1,731	597
Pedaling rate (rpm)								
40	941	307	307	104	682	225	974	318
60	905	241	295	70	661	175	938	249
80	872	220	299	78	606	186	906	227
100	960	226	458	229	713	174	1,000	241
Saddle height								
Low	1,030	362	482	194	753	271	1,070	380
Mid	905	241	295	70	661	175	938	249
High	616	158	185	80	459	117	642	163
Foot position								
Anterior	905	241	295	70	661	175	938	249
Posterior	1,052	246	301	69	774	174	1,091	254

* Fcp = patellofemoral compressive force.

^b Fcq = compressive force between quadriceps tendon and femoral intercondylar groove.

^c Fp = patellar-tendon strain force.

^d Fq = quadriceps-tendon strain force.

CONCLUSIONS

The compressive forces (Fcp and Fcq) induced during ergometric cycling generally are lower than that for most other daily activities and exercises. The magnitudes of patellofemoral joint forces (Fp, Fq, Fcp, and Fcq) during cycling are almost independent of the subject's body weight because of sitting on the saddle. Cycling, therefore, might be preferable for patients who are obese. Finally, the patellofemoral joint forces change significantly as a result of changes in ergometric work load or saddle height, but not with pedaling rate or foot position.

Acknowledgments. This study was supported by grants from the Swedish Medical Research Council (5720) and the Karolinska Institute, Stockholm, Sweden.

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