

Force and repetition in cycling: possible implications for iliotibial band friction syndrome

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Abstract

This study examined force and repetition during simulated distance cycling with regard to how they may possibly influence the on-set of the overuse injury at the knee called iliotibial band friction syndrome (ITBFS). A 3D motion analysis system was used to track lower limb kinematics during cycling. Forces between the pedal and foot were collected using a pressure-instrumented insole that slipped into the shoe. Ten recreational athletes (30.6 ± 5.5 years) with no known history of ITBFS participated in the study. Foot–pedal force, knee flexion angle and crank angle were examined as they relate to the causes of ITBFS. Specifically, foot–pedal force, repetition and impingement time were calculated and compared with the same during running. A minimum knee flexion angle of approximately 33° occurred at a crank angle of 170° . The foot–pedal force at this point was 231 N. This minimum knee flexion angle falls near the edge of the impingement zone of the iliotibial band (ITB) and the femoral epicondyle, and is the point at which ITBFS is aggravated causing pain at the knee. The foot–pedal forces during cycling are only 18% of those occurring during running while the ITB is in the impingement zone. Thus, repetition of the knee in the impingement zone during cycling appears to play a more prominent role than force in the on-set of ITBFS. The results also suggest that ITBFS may be further aggravated by improper seat position (seat too high), anatomical differences, and training errors while cycling.

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1. Introduction

Iliotibial band friction syndrome (ITBFS) is a commonly occurring sports related injury at the knee. ITBFS is associated with overuse in long distance runners, cyclists, and military personnel [1]. It is caused by friction of the iliotibial band (ITB) across the lateral femoral epicondyle during sporting activities [2,3]. The ITB is ‘...a thickened strip of fascia that extends from the iliac crest to the lateral tibial tubercle and receives part of the insertion of the tensor fascia lata and gluteus maximus [4].’ Thus, the ITB reaches from the hip to the knee and its position relative to the femur changes

in angle as the knee joint goes through flexion and extension. The ITB lies anterior to the lateral femoral epicondyle when the knee is in full extension. This position quickly changes during knee flexion. In fact, at 30° of flexion, the ITB lies behind or on the lateral femoral epicondyle [5]. Thus, the pain caused by ITBFS occurs when the knee is flexed between 0° and 30° , but especially at 30° , where the posterior fibers of the ITB experience the greatest friction [3]. The area where the ITB and lateral femoral epicondyle touch is known as the impingement zone.

Previous research related to ITBFS has focused primarily on knee kinematics. However, it is important to recognize that ITBFS is dependent on a kinetic quantity: friction. Friction is a force that acts at the interface between surfaces and is oriented opposite to the direction

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of motion [6]. In addition, the magnitude of the friction force is directly proportional to the reaction force between the surfaces. In the case of the ITBFS, the reaction force is produced at the contact point between the ITB and the lateral femoral epicondyle. The reaction force is supplied by the tensor fascia lata and the gluteus maximus. Therefore, friction force will increase with increased muscular tension or decrease with a reduction in muscular tension.

ITBFS is most prevalent in runners and thus the majority of research has been related to running. Cavanagh and LaFortune [7] found that distance runners produced a maximum vertical force of approximately 1800 N, a maximum braking force of 600 N, and maximum mediolateral force of 180 N for a 4.5 m s^{-1} jogging pace. Messier et al. [8] reported that at 3.4 m s^{-1} , normal healthy distance runners had a maximum vertical ground reaction force of 1700 N while runners with ITBFS had a maximum vertical ground reaction force of 1580 N.

Although most common in distance runners, there is a growing number of cyclists with ITBFS [3]. ITBFS accounts for approximately 15% of all overuse injuries at the knee in cycling [3]. The high number of revolutions of the bicycle cranks and tightness of the ITB resulting from muscular effort can result in inflammation of the ITB during cycling. Additionally, a snapping of the ITB may occur as it slides over the lateral femoral epicondyle of the femur, typically when the crank is approaching bottom center [3]. In cycling, the symptoms of ITBFS often emerge as a tenderness of the ITB at the knee. In addition, swelling may occur over the lateral femoral epicondyle and a stabbing or burning pain may be experienced.

Several studies have investigated forces during cycling [9–11] while others have studied causes of ITBFS in cyclists [3,12], but none have related the foot–pedal forces and repetition with ITBFS. Takaishi et al. [11] calculated peak pedal force for various cycling cadences in both competitive and noncompetitive cyclists and determined that noncompetitive cyclists preferred a lower cadence (70 RPM) than competitive cyclists (80–90 RPM) for a moderate rate of work intensity (150 W). This resulted in competitive cyclists having lower peak pedal forces (300 N) than noncompetitive cyclists (350 N) at 200 W. Takaishi et al. also demonstrated that, in general, higher cadence resulted in lower peak pedal force. Raasch et al. [10] examined forces of maximum-speed start-up pedaling for cyclists and documented a maximum tangential force at the pedal of approximately 700 N at 90° crank angle (0° being the beginning of the down stroke) and a maximum radial force of approximately -700 N at 150° . Davis and Hull [9] reported pedal loading for an experienced amateur cyclist and showed that a maximum vertical force magnitude of 320 N occurred at approximately

100° of crank angle during an 80 RPM cadence and average pedal power of 180 W.

As mentioned earlier competitive cyclists routinely practice at higher cadences of 80–90 RPM as compared with non-competitive cyclists who typically ride at a cadence of approximately 70 RPM. This difference is due to the fact that competitive cyclists adopt a more efficient style of riding that minimizes power requirements over long distances and improves muscular and cardiovascular endurance. Takaishi et al. [13] reported that to maintain a constant average power output over a workout, faster cadences are more efficient. Increased pedal cadence requires reduced pedal torque and therefore reduced muscular forces. Hence, riding at higher cadences minimizes muscle force and neuromuscular fatigue. Neptune and Hill [14] developed a theoretical endurance cycling model that suggested that pedaling rate selection is a direct outcome of minimizing neuromuscular fatigue related quantities, and that a cadence of 90 RPM minimized fatigue.

The present study was undertaken to gain a better understanding of the mechanics of cycling and ITBFS. Distance cycling training conditions were simulated because these cyclists, in general, are at higher risk for the overuse injury of ITBFS. This study made use of plantar-pressure technology to measure the foot–pedal forces directly during the activity, thereby allowing the subjects to wear their own footwear and eliminating the need for developing a force instrumented pedal system. Foot–pedal force, repetition, and impingement time in a simulated distance cycling situation (maintaining 80–90 RPM) were investigated to gain insight as to their possible roles in relation to ITBFS. Furthermore, total time of ITB contact (rubbing) over the lateral epicondyle was calculated based on this experimental data and documented values of knee flexion and ITB contact. The findings of this study are discussed in comparison to those previously reported by Davis and Hull [9], Raasch et al. [10], Takaishi et al. [11], Cavanagh and LaFortune [7], and Messier et al. [8] as they relate to ITBFS.

2. Methods

2.1. Subjects

Six men and four women (age: 30.6 ± 5.5 years; height: 177.4 ± 6.4 cm; mass: 75.4 ± 15.9 kg) participated in this study. All participants were healthy and had no known history of ITBFS or any other lower extremity disorders. Furthermore, all participants in the study were recreational athletes working out an average of 2.5 times per week.

2.2. Instrumentation

All data were collected at the Good Samaritan Hospital Orthopaedic Research Laboratory in West Palm

Beach, FL. A Sirtus (Specialized Bicycles, Morgan Hill, CA) bicycle mounted on a Magturbo trainer (Minoura USA, Hayward, CA) was utilized for this study. Participants were instructed to ramp up to a speed corresponding to 80–90 RPM in a preset gear and maintain that speed while data were collected. A bicycle computer provided feedback on crank rotational speed.

Lower limb kinematics were obtained with a Motion Analysis Corporation 6-camera video kinematic measurement system and EVA HiRes Data Acquisition Software (Motion Analysis Corporation, Santa Rosa, CA) at a sampling rate of 180 Hz. Reflective markers were placed on the lateral malleolus, calcaneus, toes (between second and third metatarsal heads), lateral mid-calf, lateral knee joint line, lateral mid-thigh, and ASIS of each leg. An additional marker was placed on the pedal shaft. This set of markers captured the 3D kinematics of the thigh, leg, foot, and pedal, and in particular allowed knee flexion, hip tilt, and pedaling cadence to be determined.

Foot–pedal forces were acquired with a portable Datalogger (Paromed Medizintechnik, Neubeuern, Germany) and an instrumented shoe insole, which can record forces at 16 points on each foot. Preliminary trials showed that the forces recorded at the pressure sensors under the heel added little to the total force under the foot. Consequently, only the 11 sensors measuring pressure under the anterior portion of the foot were used. This allowed the open channels to be used to synchronize the kinematic and kinetic data. These forces, representing the normal force component, were sampled at a frequency of 180 Hz. Fig. 1 shows a photograph of the experimental set-up.

A single event needed to be identifiable on both measurement systems (force and motion measurement) so that the data could be synchronized. To accomplish this, an additional reflective marker (monitored with the motion analysis system) and an accelerometer (data measured via the Datalogger) were attached to a flexible card at the bottom dead center of the crank. Each time the crank passed bottom dead center on the down stroke (180°) and hit the flexible card; the event was recorded on each system.

2.3. Protocol

Prior to participation, each subject read and signed an informed consent agreement approved by the Institutional Review Board of the University of Florida. Experimental procedures were then explained to each subject and a cycling experience questionnaire was administered. Lower extremity anthropometric measurements were taken. Kinetic and kinematic data were then collected in the following steps:

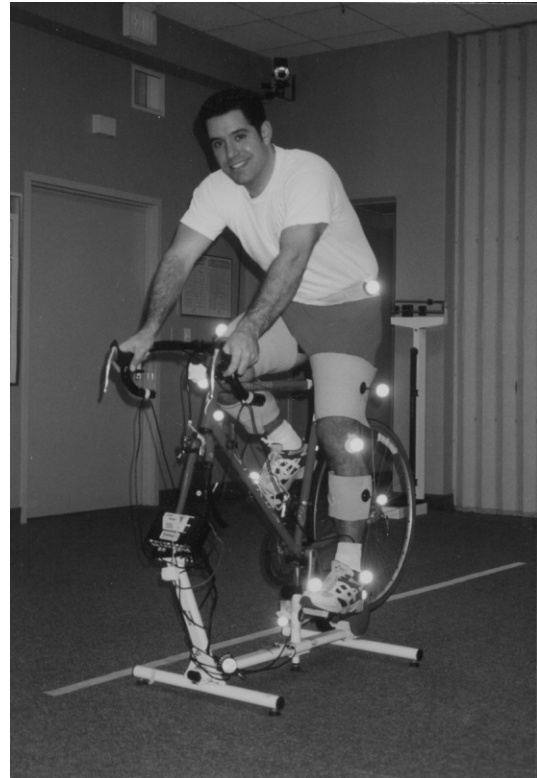


Fig. 1. Experimental set-up showing bicycle mounted on trainer, participant with attached reflectors, Paromed force detection equipment (front forks of bicycle and insole of shoe), and one of six cameras used for 3D motion detection.

(1) Reflective markers were applied over the bony landmarks and force sensing insoles were placed in the shoes of each participant.

(2) Safe cycling standards dictate that the seat height be adjusted so that the knee is in 15–30° of flexion for the pedal at bottom dead center. Thus, seat height was determined as each subject sat on the seat with the foot and pedal at bottom dead center. At this point, the knee angle was measured using a goniometer. Seat height was adjusted so that the knee angle was 25–30°. After seat adjustments, subjects were asked to pedal slowly to ensure that the seating was comfortable and there was little or no pelvic tilt during slow cycling.

(3) Each subject was given a 2-min warm up period followed by a 5-min stage of pedaling at a set cadence (80–90 RPM) in the gear corresponding to approximately 280 W maximum power at 90° crank angle. During this phase, five (4-s duration) data collections were obtained at 180 Hz. Two minutes were then provided for the test subjects to cool down.

(4) A sixth data collection was then performed with the participant's legs hanging freely (feet off the pedals). This data set provided the sensor forces resulting from fastening the shoe to the foot. These forces were later

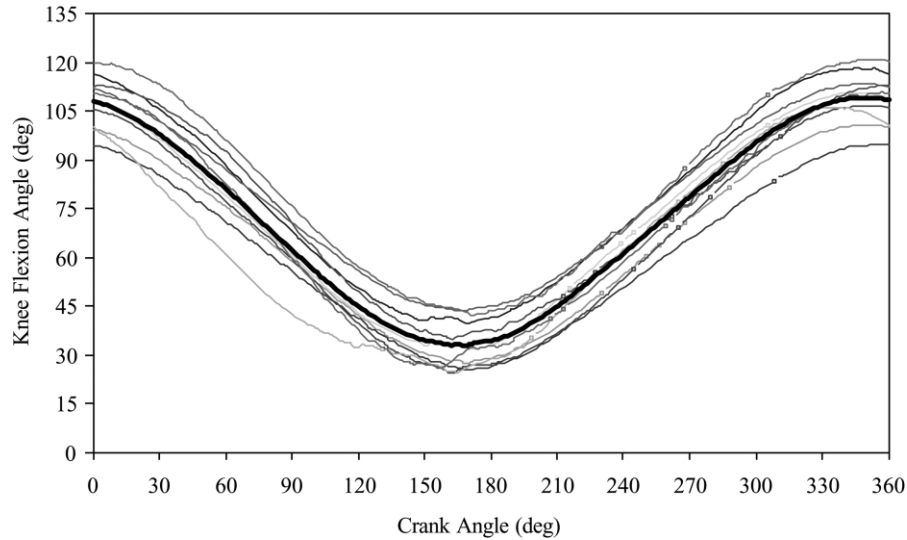


Fig. 2. Knee flexion angle versus crank angle for 88 RPM cycling (280 W maximum power, right pedal). Average for each subject and overall average for all 10 subjects (in bold). Zero degrees is top dead center of pedal stroke.

subtracted from the foot–pedal forces obtained during the trials.

(5) The reflective markers and insoles were removed.

2.4. Data processing

Force and acceleration data from the Datalogger were converted to spreadsheet compatible format after collection. Only the right foot data were analyzed. Data from each of the sensor channels were corrected for the static forces resulting from tying the shoe around the foot. The true sensor forces were determined by subtracting the force at each sensor associated with tying the shoe to the subject's foot from the magnitude of the force at each sensor. Summation of the force at all 11 sensors provided the total foot–pedal force magnitude seen by the sensors. Having calculated the total foot–pedal force for each frame, the accelerometer data allowed the bottom dead center position of the crank to be determined. Hence, the data could be separated into complete revolutions of the crank. Foot–pedal force data for each crank cycle were normalized in order to compare an equal number of frames among participants. The foot–pedal forces for the first full crank revolution of each of the 5 data sets (per subject) were averaged to acquire foot–pedal force as a function of crank angle for each subject.

Markers identifying bony landmarks were tracked through the EVA software. The 3D marker data were subsequently imported into Ortho Trak (Motion Analysis Corporation, Santa Rosa, CA) gait analysis software to obtain the lower limb kinematics. Specifically, knee and ankle flexion, hip tilt and pedal cadence were calculated and exported to a spreadsheet. Similar to the procedure for force data, the first full crank revolution of each

data set was normalized and then averaged across the 5 trials for each subject. Knee flexion angle and hip angle versus crank angle were obtained.

3. Results

3.1. Knee flexion angle versus crank angle

Fig. 2 shows knee flexion angle versus crank angle for one complete revolution (360°) of the bicycle crank for cyclists riding at 88 RPM and 280 W maximum power. A crank angle of 0° represents top dead center of the bicycle crank revolution. The average for each of the 10 subjects is shown as well as the average for all subjects. Maximum knee flexion (~110°) occurred for crank angles between 340° and 0°. Minimum knee flexion angles of 30–35° (32.9±7.2°) were recorded at crank angles from 160° to 180°.

During saddle height adjustment prior to the experiment, bottom dead center of the crank corresponded to knee flexion angles of 25–30°. During the cycling tests, the knee flexion angle only reached 30–35°. Further investigation indicated that lateral pelvic tilt (rocking side to side) contributed approximately 5–6° to this knee flexion angle increase when the crank was at bottom dead center. Rocking occurs during cycling and is exaggerated at higher speeds.

3.2. Foot–pedal force versus crank angle

Fig. 3 shows the foot–pedal force versus crank angle for one complete revolution of the bicycle crank for participants riding at an average of 88 RPM and a 280 W maximum power. Again, a crank angle of 0° represents the top dead center of the bicycle crank revolution.

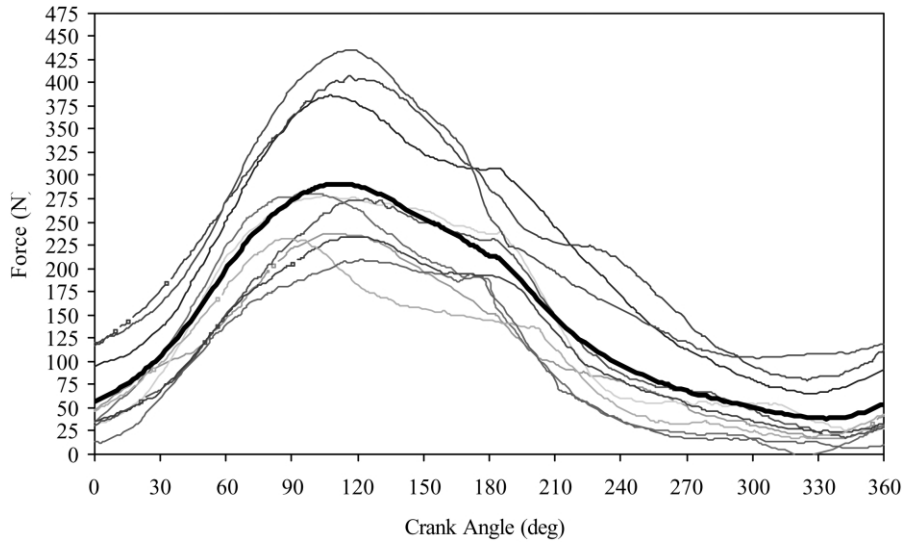


Fig. 3. Foot–pedal force vs. crank angle for 88 RPM cycling (280 W maximum power, right pedal). Average for each subject and overall average for all 10 subjects (in bold). Zero degrees is top dead center of pedal stroke.

The average for each of the ten subjects is shown as well as the average of all 10 subjects. Of particular importance is that, on average, the peak foot–pedal force of 290.9 ± 84.2 N occurred at a crank angle of approximately 110° . The crank angle and peak foot–pedal force are consistent with results from Davis and Hull [9] and Takaishi et al. [11] who reported peak pedal forces of 320 and 300–350 N, respectively. Thus, the relation of foot–pedal force to crank angle in this experiment is validated by results of previous research.

3.3. Foot–pedal force versus knee flexion angle

Fig. 4 depicts the foot–pedal force as a function of the knee flexion angle for a typical distance cycling

cadence of 88 RPM. Also depicted on the graph is the ITB impingement zone. It is important to note that the impingement zone and the foot–pedal force as a function of knee flexion will vary between individuals. Hence, there may be more or less overlap of the foot–pedal kinetics into the impingement zone. From these experimental results, conclusions about the potential effects of force and repetition on ITBFS during cycling can be discussed.

4. Discussion

The causes of ITBFS in cycling are varied. Holmes et al. [3] described causes of ITBFS as anatomical: leg length discrepancies, varus knee alignment or excessive

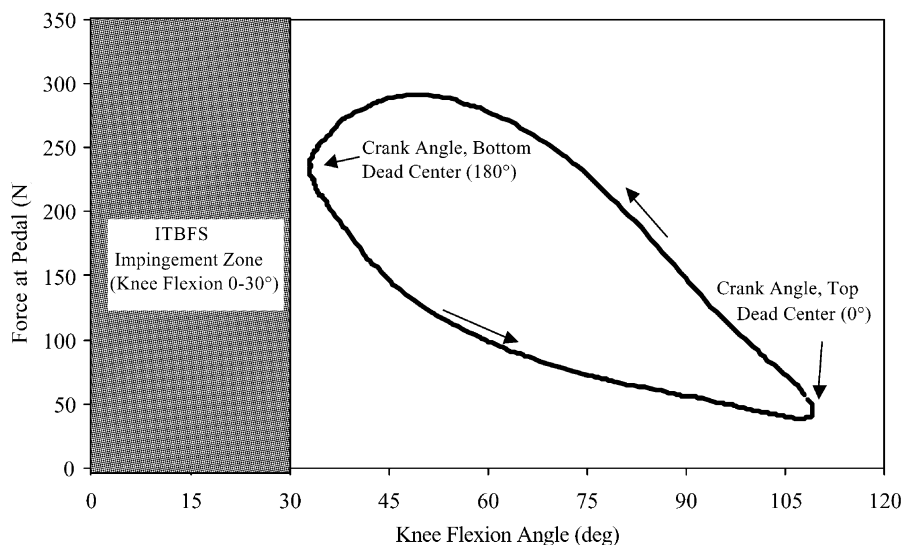


Fig. 4. Foot–pedal force vs. knee flexion angle for 88 RPM cycling (280 W, maximum power, right pedal). Overall average for 10 subjects.

pronation, and external tibial rotation of more than 20°. Most of these anatomical differences result in a tightening of the ITB, and thus increased friction at the impingement area. Additionally, riding position plays a role in causing ITBFS. A seat that is too high causes excess stretch of the ITB as can improper foot position on the pedal, rigid clipless pedals, and excessively toed in cleats. Furthermore, training changes in cycling, such as sudden increases in mileage, hills, and time trials, can contribute to ITBFS. Thus, it appears that kinematics and kinetics play roles in ITBFS.

The current study allowed the magnitude of the foot–pedal forces during cycling to be analyzed with respect to knee angle and crank angle. Thus, referring to Figs. 2–4 and knowing that the impingement zone (ITB and lateral femoral epicondyle contact) is 0–30°, it is clear that, during cycling, the minimum knee flexion angles experienced by our riders just entered the impingement zone of the ITB where rubbing occurs. The forces were found to be 230.8 ± 64.8 N at the foot–pedal interface in the area of the impingement zone. For comparison, Cavanagh and LaFortune [7] found that the peak vertical force at 0–30° knee flexion (first 75 ms of foot contact with ground [2]) was approximately $2.2 \times$ body weight, or approximately 1315 N for a 61-kg subject running at approximately 4.5 m s^{-1} . Messier et al. [8] found that a peak vertical force at 0–30° knee flexion was approximately $1.75 \times$ body weight, or approximately 1200 N for a 70-kg healthy runner with a pace of 3.4 m s^{-1} . Thus, the normal force at the foot for cycling is only 17–19% of the vertical force at the foot for aggressive jogging while the ITB is in the impingement zone. The reduced force at the foot will result in lower joint and muscle forces in the lower extremity. Reduced muscle forces will likely be associated with reduced tension in the ITB and less friction between the ITB and the lateral femoral epicondyle.

In running studies performed by Orchard et al. [2], results showed time spent in the impingement zone was approximately 75 ms during foot contact with the ground. The cycling results for this experiment found 38 ms of impingement contact per revolution of the crank (assuming 20° of 360° revolution is in the impingement zone). Thus, less impingement time between the ITB and the femoral epicondyle occurs per cycle in biking than in running.

Although less impingement time per cycle occurs in cycling than in running, the amount of cycles performed for a given work out must be noted. For an athlete jogging at 4.5 m s^{-1} and a 1-m stride (2 m between right foot to right foot ground strike), the athlete will hit the impingement zone on a particular leg (with ground reaction force applied) roughly 4800 times for a 10-km jog. In comparison, a cyclist at 88 RPM on a 1.25-h ride will hit the impingement zone approximately 6600 times. Assuming these running and cycling work-

outs are equivalent (4 km cycled for every 1 km jogged), cyclists would experience 30–40% more ITB impingement occasions for a given workout. Although the cyclist experiences more impingement events, the total time spent in the impingement zone over the entire cycling workout (250 s) is less than the total time spent in the impingement zone during running (330 s).

We suggest that repetition is the primary contributor in causing ITBFS in cycling, while force is secondary. This suggestion is justified since the magnitude of the foot–pedal force during cycling is only one-fifth the magnitude of the ground reaction force during running when the ITB is in the impingement zone. Additionally, while cyclists experience more ITB impingement events for equivalent workouts the time per cycle and the total time spent in impingement is less. Cyclists, however, still suffer from ITBFS.

Why does ITBFS occur at all in cycling considering the low force, decreased impingement time per cycle, and smooth force transitions (when compared to jogging)? As mentioned earlier, anatomical differences often lead to the tightening of the ITB around the femoral epicondyle, causing more friction. Other causes of ITBFS are often related to riding position and training changes. This study emphasizes the effect these contributors can have in the on-set of ITBFS. As a prime example, Fig. 4 shows that minimum knee flexion tends to be approximately 30–35°. If seat position was set improperly (too high or too far back), the minimum knee flexion angle could easily dip much farther into the 0–30° impingement zone, thus causing increased ITB rubbing. This is also the case for an anatomical difference, such as a leg length discrepancy, that causes the shorter leg to overextend and ITB impingement to be sustained longer. Thus, anatomical differences and seat position are supported by this research as causes of ITBFS in cycling.

The results of this study can offer some clinical guidelines following knee surgery. Bicycle and cycling exercises are routinely used in order to encourage range of motion (ROM) after total knee replacement surgery. Often such exercise is used when the patient's maximum ROM is in the range of 90–110°; and is sometimes accompanied by lateral knee pain. Additionally, it is routinely recommended for patients in rehabilitation after knee surgery to keep the seat high so as not to force flex the knee. These patients are also encouraged to cycle at a low resistance for a large number of repetitions. The results of the present study suggest that such rehabilitation measures may have deleterious effects resulting in ITBFS. For example, to obtain continuous cycle motion with reduced ROM the seat must be raised to accommodate the patient's maximum flexion ability. Raising the seat, however, results in overextension and possible loss of contact when the pedal is in the bottom position. In this situation the

patient will be spending a significantly greater amount of cycle time working with the knee in an extended position. Thus, the ITB enters far into the impingement zone due to the overextension and spends a greater amount of time there for each revolution. The situation is further aggravated by the fact that these patients will not be cycling at a high cadence, and will therefore not gain the benefit of increased lateral tilt which limits movement of the ITB into the impingement zone. For the same reasons, intentionally setting the seat too high to prevent force flexion during rehabilitation would most likely stretch the ITB, on both the involved and uninvolved sides, with possible negative side effects such as discomfort and ITBFS. While these scenarios suggest that ITBFS may result from rehabilitation following knee surgery, it must be emphasized that ITBFS usually occurs as a result of overuse. Thus, if a patient is cycling short distances (1–3 miles), the likelihood of experiencing ITBFS is low. Additionally, it is unlikely that the intensity and magnitude of rehabilitation would permanently damage the ITB in the short term. In fact, the benefit of gaining ROM early in rehabilitation would, in general, outweigh any potential problems from ITB friction. If, however, the patient has certain anatomical conditions (leg length discrepancies, varus knee alignment or excessive pronation, and external tibial rotation of more than 20°), he/she will be more inclined to experience ITBFS. In this case of certain anatomical conditions, raising the seat to accommodate reduced ROM or to prevent force flexion of the knee, may aggravate the ITB more quickly and increase the likelihood of ITBFS. In summary, since ITBFS is an overuse injury it is unlikely that individuals recovering from surgery will experience the number of repetitions necessary to induce ITBFS if cycle rehabilitation is used in moderation (couple miles at a time), especially if the seat height is correctly set and the patient does not present with certain anatomical conditions. Consequently, proper rehabilitation technique should be the first concern, not the onset of ITBFS. If pain does occur, the rehabilitation protocol can easily be modified by selection of a different exercise. Pain due to ITBFS stops soon after the given exercise is stopped, thus long-term effects would be minimal if ITBFS did occur.

5. Conclusions

The objective of the study was to determine whether foot–pedal force or knee flexion repetition was more likely to result in the on-set of the overuse injury ITBFS during cycling. Using a novel, plantar-pressure measurement technique this research has shown that foot–pedal

forces during cycling are only a small fraction of the ground reaction forces found during running in past studies. Furthermore, it has been shown that during cycling the ITB spends less per cycle time and less total time in the impingement zone for similar workouts. This research supports the conclusion that force may not play a role in causing ITBFS for cycling. Instead, repetition, anatomical differences, improper cycle set-up, and training habits may be the more likely contributors to the on-set of ITBFS. Further studies of athletes with a history of ITBFS would serve as a strong comparison in investigating the role of force in cycling and the on-set of ITBFS.

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References

- [1] Kirk LK, Kuklo T, Klemme W. Iliotibial band friction syndrome. *Orthopedics* 2000;23(11):1209–1214.
- [2] Orchard JW, Fricker PA, Abud AT, Mason BR. Biomechanics of iliotibial band friction syndrome in runners. *Am J Sports Med* 1996;24(3):375–379.
- [3] Holmes JC, Pruitt AL, Whalen NJ. Iliotibial band syndrome in cyclists. *Am Orthop Soc Sports Med* 1993;21:419–424.
- [4] Lindenberg G, Pinshaw R, Noakes TD. Iliotibial band friction syndrome in runners. *Physician Sports Med* 1984;12(5):119–130.
- [5] McNicol K, Tauton JE, Clement DB. Iliotibial track friction syndrome in athletes. *Can J Appl Sport Sci* 1981;6(2):76–80.
- [6] Hall SJ. *Basic biomechanics*. Boston, MA: McGraw-Hill, 1999.
- [7] Cavanagh RP, LaFortune MA. Ground reaction forces in distance running. *J Biomech* 1980;13:397–406.
- [8] Messier SP, Edwards DG, Martin DF, Lowery RB, Cannon DW, James MK, Curl WW, Read HM, Hunter DM. Etiology of iliotibial band friction syndrome in distance runners. *Med Sci Sports Exercise* 1995;27(7):951–960.
- [9] Davis RR, Hull ML. Measurement of pedal loading in bicycling: II. Analysis and results. *J Biomech* 1981;14(12):857–872.
- [10] Raasch CC, Zajac FE, Ma B, Levine WS. Muscle coordination of maximum-speed pedaling. *J Biomech* 1997;30(6):595–602.
- [11] Takaishi T, Yamamoto T, Ono T, Ito T, Moritani T. Neuromuscular, metabolic, and kinetic adaptations for skilled pedaling performance in cyclists. *Med Sci Sports Exercise* 1998;30(3):442–449.
- [12] Pena N. The critical joint. *Bicycling* 1991;74–80.
- [13] Takaishi T, Yasuda Y, Moritani T. Neuromuscular fatigue during prolonged pedaling exercise at different pedaling rates. *Eur J Appl Physiol* 1994;69:154–158.
- [14] Neptune R, Hill M. A theoretical analysis of preferred pedaling rate selection in endurance cycling. *J Biomech* 1999;32:409–415.