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A 3-D Biomechanical and EMG Analysis of Three Mountain Bike Pedal Designs

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A 3-D BIOMECHANICAL AND EMG ANALYSIS OF THREE MOUNTAIN BIKE PEDAL DESIGNS

by

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A 3-D BIOMECHANICAL AND EMG ANALYSIS OF THREE MOUNTAIN BIKE PEDAL DESIGNS

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The problem of this study was to compare the lower limb kinematics and EMG activity of three bicycle pedal designs. The pedals investigated were a flat pedal platform and two different clip-in pedal designs, float with friction (FF) and spring recentered float (SF). The FF pedals offered 8° of rotational float and the SF pedals offered 10° of rotational float and 3 mm of medial-lateral translation. Sixteen healthy male and female volunteers between the ages of 18 and 29 performed five complete cycles of motion, beginning and ending at ATP, at two cadences under each of the three pedal conditions. Pedal design produced significant differences in lower limb kinematics. Subjects displayed significantly larger ankle angles with SF pedals compared to flat pedals during push phase. FF pedals produced larger varus/valgus angles than flat pedals. Subjects displayed a varus angle throughout the entire crank cycle. No significant differences across muscles existed for the different pedal designs. Cadence, pedal design, and phase interact to influence the behavior of GAS and ATIB. ATIB acitivity was different among pedals at each cadence. FF and flat pedals produced larger EMG areas at 90 rpm, while SF pedals produced larger EMG area at 60 rpm.

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CHAPTER I

INTRODUCTION

Bicycling has long been a popular form of recreation and transportation. Recently, its popularity has skyrocketed due to enhancements in technology and increasing competitive and recreational opportunities. Suspension systems, helmet designs, and pedal designs are examples of some of the technological innovations that have advanced the sport of cycling. However, scientific information concerning these product changes is needed to aid the consumer. One piece of equipment that is often overlooked is the pedal. Three basic pedal designs exist: (1) a flat pedal deck; (2) a flat pedal mounted with a toe cage; (3) and a clipless pedal which secures the rider's foot to the pedal, similar to a ski binding.

The flat pedal deck is the most basic design. It allows the cyclist to move through an uninhibited range of motion (ROM): inversion, eversion, internal and external tibial rotation, and anterior-posterior and medial-lateral translation of the foot on the pedal deck. With this pedal, the foot is not attached to the pedal, so the rider is able to remove the feet from the pedals freely. However, this design limits force generation during pedaling to only the downstroke, or push phase of a complete cycle of motion.

A flat pedal may be fitted with a cage to help keep the rider's foot in a more stable position on the pedal. The toe clip design was an early alteration aimed at improving pedaling performance. Toe clips improved performance by allowing the rider to pull the pedal through the upstroke, and by stabilizing the foot on the pedal to allow more efficient transfer of energy from the foot to the pedal.

Clipless pedals are widely used in competitive cycling. This design allows the rider to lock his or her foot into the pedal. Theoretically it creates the most stable foot-pedal interface, which should allow the rider to apply torque to the crank more efficiently. However, this design can restrict natural foot movement in pedaling when compared to the other pedal designs. The restriction of ROM could alter the cyclist's natural pedaling gait, leading to overuse injuries (Boyd, Neptune, & Hull, 1997). Three popular clipless pedal designs exist: fixed float, free float, and spring-recentered float.

Fixed float pedals restrict movement at the foot/pedal interface, allowing movement through a limited range of motion. These pedals will often allow rotation around a fixed point on the pedal. This type of movement is referred to as rotational float. Free-float pedals allow free movement through a limited range of motion. Increased movement results in a less stable foot/pedal interface.

Clipless pedals also provide resistance to float. This feature is designed to stabilize the foot/pedal interface and increase the efficiency of the energy transfer between the foot and the pedal. Two common types of float are spring-recentered float and float with friction. Spring-recentered pedals allow free movement of the foot upon the pedal, but a spring-loaded mechanism will center the foot over a fixed point on the pedal. The neutral position is usually located near the center of the pedal deck.

As the foot rotates throughout the crank cycle, the spring mechanism returns the foot to its neutral position on the pedal. Some pedals feature float with friction. This design allows foot movement against resistance, but the foot is not recentered following movement.

Current clipless pedal designs allow the cyclist movement through limited range of tibial rotation around the foot/pedal interface. Boyd et al. (1997) noted that cyclists displayed varying degrees of tibial rotation, inversion end eversion, and medial-lateral translation during pedaling. When a cyclist is forced to alter the kinematics of their pedaling gait, joint loads are created as a result of the constraint on the range of motion. Knee joint constraint loads were reduced in cyclists who pedaled on a clipless style pedal that permitted motion at the foot/pedal interface (Boyd et al., 1997). Recent findings suggest that additional motion could reduce injuries by allowing cyclists to pedal using their natural pedaling gait throughout the crank cycle.

When cyclists utilize their natural pedaling gait, they are able to apply torque more evenly throughout the crank cycle. Because the cyclist's foot is locked into the pedal, the cyclist is able to apply force more effectively during the upstroke. By generating more torque during the pull phase, crank arm velocities will remain more consistent between push and pull phases.

Statement of the Problem

The problem was to compare the efficiency of three bicycle pedal designs, with regard to their effect on muscle activity and the fluidity of the crank cycle. Biomechanical and electromyographical data were compared to determine which pedal design produced the most efficient application of muscular force.

Purpose of the Study

The purpose of this study was to provide cyclists with information on the impact that pedal design can have on the biomechanics of cycling. Cyclists are faced with decisions on pedals without knowing how the pedals affect muscle action, cycling gait, and the likelihood of injury.

Delimitations

The study was delimited to the following:

1. Subjects were Western Michigan University, male and female student volunteers between the ages of 18 and 29 years of age.

2. Subjects were classified as recreational cyclists who rode for fitness and rode 3–5 times or less per week.

3. Subjects rode on a frame that was mounted to a Fluid+ trainer, CycleOps, New York.

4. All pedals were tested at 60 and 90 rpm. Subjects repeated each pedal condition and each pedal speed over five cycles or trials.

5. EMG data was collected for the vastus medialis, rectus femoris, vastus lateralis, biceps femoris, semimembranosis, semitendinosis, gastconemius, and soleus muscles. Semimembanosis and semitendinosis were monitored jointly as the medial hamstrings.

6. Peak Motus, Peak Performance Technologies, Inc., Englewood, CO, was used to measure the kinematic variables by digitizing videotaped images of the subject pedaling during a steady state.

7. A Myosystem 2000, Noraxon, Pheonix, AZ, measured the EMG response of each muscle.

Limitations

The study was limited to the following:

1. Subjects were opportunistically, not randomly, selected. Therefore, the external validity of the study may be compromised.

2. Subjects were familiar with one pedal type but not the other two types. The familiarity of pedal type may not have been equal for each pedal studied.

3. Subjects pedaled on the same bike. This ensured that the geometric orientation of the frame was similar for all subjects.

Assumptions

The researcher assumed the following:

1. Subjects adapted easily to each pedal and to riding on an ergometer.

2. The video camera and EMG were functioning properly, assuring that all data were properly synchronized.

Hypotheses

This study was designed to examine the following research hypotheses:

1. Lower extremity angular displacement will be different for the flat, clip, and time pedals.

2. A greater EMG area will occur during the push phase for the flat pedal compared to the clip or time pedals.

3. A greater EMG area will occur during the pull phase for the clip and time pedals than for the flat pedal.

4. Similar muscle action was expected between the clip and time pedal conditions for both cadences and both phases of motion.

Definition of Terms

The following terms were defined for clarification and understanding:

1. *Absolute Bottom Point (ABP)*: The lowest point the pedal reaches during the crank cycle. ABP is achieved when the crank arm is downward and perpendicular to the horizontal. ABP will be associated with the halfway point of a cycle and will represent a point 180° within a complete cycle.

2. *Absolute Top Point (ATP):* The highest point the pedal reaches during the crank cycle. ATP is achieved when the crank arm is upright and perpendicular to the

horizontal. ATP will be associated with the start of a cycle and will represent 0° of a complete cycle.

3. *Crank cycle:* One revolution of the pedal or 360° of circular motion about the crank spindle axis. A crank cycle consisted of two phases: upstroke and downstroke.

4. *Downstroke:* Begins at ATP, and ends at ABP or when the pedal has traveled from 0° to 180° within the crank cycle. This is referred to as the push phase.

5. *Foot-pedal interface:* The area of contact between the foot and the pedal deck.

6. *Upstroke:* Begins at ABP and ends at ATP, or when the pedal has traveled from 180° to 360° within the cycle. This is referred to as the pull phase.

CHAPTER II

REVIEW OF RELATED LITERATURE

History of the Problem

Clipless pedals were introduced in the late 1980s. These pedal designs were determined to boost performance ("Clipless Pedals Boost Performance," 1990). Shortly after the pedals were introduced, cyclists began to present a variety of lower extremity overuse injuries (Ruby & Hull, 1993). Original clipless pedal designs secured the cyclist's foot to a fixed point on the pedal. When the foot is fixed to the pedal, cyclists can experience alterations in their natural kinematic patterns. These alterations result from restricted foot movement and increased loads at the knee joint. Increased knee loads can lead to overuse knee injuries (Holmes, Pruitt, & Whalen, 1993; Ruby & Hull, 1993). Movement was restricted as a result of the constraint mechanism on the pedal not allowing movement at the foot/pedal interface. Researchers have investigated pedal designs that allow different types of movement at the foot/pedal interface and how these designs can reduce joint loads (Ruby & Hull, 1993).

Data collected on overuse injuries among runners indicate that certain factors which alter the gait patterns of runners may increase their likelihood of injury. Shoe design, running surface, training intensity, and training volume are factors that commonly contribute to overuse injuries (Arnheim & Prentice, 1993). In cycling, the rider's feet do not come in contact with the ground. All propulsive forces are delivered to the crank, by the foot, at the foot/pedal interface. Reaction forces are delivered from the bike to the cyclist at the wrists, the buttocks, and the foot/pedal interface. The pedals serve as the training surface.

Training volume can often be very high; many competitive cyclists may train up to 4 or 5 hours a day. Competitive cyclists pedal at a cadence of 90–110 rpm (Marsh & Martin, 1997). At that rate, one training session could produce 30,000 crank cycles. Changes in training intensity or cycling surface such as pedaling in a fixed gear or up hills can create patellar loading and lead to overuse knee injuries (Holmes et al., 1993). Given the high-volume of repetitive motion in cycling, a slight alteration in pedaling kinematics can quickly lead to an overuse injury.

Early clipless pedal designs locked the rider's foot to a fixed point on the pedal deck. These models did not allow foot rotation during pedaling (Holmes et al., 1993). This type of pedal created two types of loads on the knee: (1) constraint loads created by the restricted movement, and (2) intersegmental loads created as mechanical energy is transferred to or from the shank. Pedals that allow movement at the foot/pedal interface have proven effective at reducing knee loads (Boyd et al., 1997).

Boyd et al. (1997) determined that a pedal design that allowed 10° of abduction/adduction and 10° inversion/eversion was effective at reducing knee loads. The authors defined abduction/adduction as the rotation of the foot about a fixed point on the pedal deck. Data indicated that abduction/adduction, or rotational float, is the most beneficial type of movement. Rotational float, often referred to as float, describes the amount of foot rotation allowed at the foot/pedal interface. Currently, clipless pedal designs allow between 0° and 20° of float.

During an investigation of lower extremity movement during pedaling, nearly all subjects displayed kinematics patterns that would be constrained by a fixed pedal deck. According Boyd et al. (1997), 7 of 11 subjects presented a range of motion in excess of that allowed by pedals permitting 4° of float. Of those subjects, 4 displayed a pedaling gait that exceeded the motion allowed by designs with 8° of float. A pedal offering 10° of rotational float appeared to accommodate foot movement in all subjects. Some designs offer rotational ranges in excess of 10°. No data could be found that could determine the effect of excessive motion on knee loads.

Kinematics of Cycling

Muscle Activity of a Crank Cycle

Popular logic for developing constraint mechanisms for pedals is that the foot will be more stable upon the pedal, and that the constraint will allow the rider to pull the pedal through the upstroke. Data indicate that these devices can favorably affect cycling performance in elite cyclists. However, untrained subjects did not experience improved performance with toe clips, possibly because they did not know how to use the devices (Wilde, Knowlton, Miles, Sawka, & Glaser, 1980).

Push Phase

As the pedal approaches ATP, uniarticular knee extensors contract to push the pedal past ATP. The rectus femoris acts as the primary hip flexor near ATP. At ATP, the gluteal muslces contract to extend the hip. Computer simulations of muscle activity during pedaling indicate that uniarticular knee and hip extensors provide much of the propulsive muscular force during the push phase (Raasch, Zajac, Ma, & Levine, 1996). Data from human subjects are consistent with the models. Peak EMG readings from human subjects indicate that peak activity for uniarticular knee extensors occurs near 45° of the crank cycle (Marsh & Martin, 1997; Raasch et al., 1997).

Hip and knee extensors continue to propel the crank beyond 90° of the crank cycle. The gastrocnemius and soleus muscles contract near 90° of the crank cycle. Peak EMG data from these muscles indicate their highest level of activity occurs between 100° and 120° of the crank cycle.

EMG data and computer simulations indicate that the medial hamstrings activate near 90° and remain active through about 250° of the crank cycle (Marsh & Martin, 1995; Raasch et al., 1997). This suggests that the hamstrings act to flex the knee to allow travel past ABP.

Pull Phase

Pull phase muscle activity begins as the pedal approaches ABP. Computer simulations suggest that the medial hamstrings contract midway through the push phase, followed by the short head of the biceps femoris and the illiopsoas muscles at

ABP. The illiopsoas provides much of the muscular energy required for the pedal to recover up through the pull phase. The rectus femoris and anterior tibialis muscles contract around 250° to 270° of the crank cycle to provide action necessary to propel the pedal through the top half of the pull phase.

Foot Movement During Pedaling

Researchers have observed that human subjects display unique kinematic patterns during bipedal ambulation (Magee, 1997). Factors that alter these kinematic patterns can create unnatural joint loads, which can lead to injury. In pedaling, the foot and ankle engage in coupled movements to facilitate force transfer. When foot movement is restricted, constraint loads are developed (Ruby & Hull, 1993).

Ruby and Hull (1993) determined that a pedal design allowing abduction/ adduction at the foot/pedal interface was effective at reducing joint loads. Subsequent investigation yielded similar results. A pedal design that permitted inversion/eversion was also effective at reducing joint loads. A pedal deck allowing both abduction/ adduction and inversion/eversion reduced joint loads at the knee. Data indicated that abduction/adduction is favorable to inversion/eversion (Boyd et al., 1997).

Foot Rotation

Rotational float is the most common type of motion available in pedals. Rotational float describes movement about a fixed point on the pedal deck. The foot is fixed to the pedal by a cleat installed on the sole of the shoe near the forefoot.

Rotation occurs around this point on the forefoot. The motion involves tibial rotation at the knee joint and coupled movement of the ankle and subtalar joints to produce circular movement of the foot about the foot/pedal interface.

In one study of cycling kinematics, subjects displayed an average ROM of 4.7° of abduction/adduction. Eight of 11 subjects remained abducted throughout the crank cycle and 3 moved from one to the other (Ruby & Hull, 1993). The maximum adduction angle was attained between 90° and 170° of the crank cycle and the maximum abduction angle was reached between 200° and 300° of the crank cycle (Neptune, Kautz, & Hull, 1997). Currently, rotational float is commonly available in 4° or 8° of float. Findings from Neptune et al. (1997) indicate a pedal that allowed 10° of float did not restrict foot movement in most cyclists.

Subtalar Movement

Two types of movement are possible at the subtalar joint: inversion and eversion. During normal walking gait, the foot moves in and out of inversion and eversion. This type of motion was shown to promote a general, nonsignificant reduction in joint loads. Boyd et al. (1997) noted that 6 of 10 subjects moved between inversion and eversion during a crank cycle. Similar research also noted several subjects moving between inversion and eversion (Ruby & Hull, 1993). These results are difficult to compare because the axis of rotation for inversion and eversion was different for each study, but they do seem to demonstrate a tendency for cyclists to move between inversion and eversion. Ruby and Hull (1993) noted that subjects tended to reach their maximum inverted foot position between 215° and 300° of the crank cycle. Maximum everted foot angle was achieved in most commonly during 0° and 90° of the crank cycle. Subtalar movement appeared to contribute to nonsignificant reductions in knee joint loads.

Foot Translation

Little evidence exists to explain the role of foot translation in pedaling. Ruby and Hull (1993) investigated foot movement on a pedal design that allowed 7 mm of medial-lateral movement across the pedal deck. This platform provided the most consistent findings, but the data were nonsignificant. All subjects displayed a foot orientation lateral to the reference point on the test pedal. Nearly all subjects displayed a ROM of less than 1 mm and remained within 1 mm of the reference point. Foot translation demonstrated no effect on reducing knee loads (Ruby & Hull, 1993).

CHAPTER III

PROCEDURES

The purpose of this study was to compare three pedal designs: (1) a flat pedal, (2) a clipless pedal with 8° of rotational float with friction, and (3) a clipless pedal with 10° of spring recentered rotational float at two pedaling intensities: 60 rpm and 90 rpm. Pedal gaits were measured by three-dimensional biomechanical and EMG analyses. This chapter is organized as follows: (a) subjects, (b) research design, (c) equipment, (d) testing procedures, and (e) statistical analysis.

Subjects

Twenty male and female subjects, 18-29 years of age, were opportunistically selected. Subjects who were selected were recreational cyclists who rode 3-5 times per week on an all-terrain bicycle for recreational or fitness purposes. Subjects signed a consent form prior to participation. This study was approved by the Western Michigan University Human Subjects Institutional Review Board (Appendix A).

Research Design

Research Variables

The design for this study was repeated measures or a block design. Subjects repeated trials nested in conditions. The study consisted of three pedal deck conditions: (1) flat, (2) float with friction (FF), and (3) spring recentered float (SF). For each pedal condition, subjects performed two exercise intensities: (1) 60 rpm, and (2) 90 rpm. Five trials or five complete cycles of motion were analyzed for each intensity level, at each pedal deck condition. Data were collected for two phases of a complete cycle: (1) push phase, and (2) pull phase.

Dependent Variables

The dependent measures, kinematic and EMG variables, are defined below:

1. Thigh angle: The angle formed by the thigh and a horizontal line passing through the hip. This angle was measured at ATP, 90°, ABP, and 270°.

2. Knee angle: The angle formed between the thigh and shank, measured on the posterior side of the extremity. This angle was measured at ATP, 90°, ABP, and 270°.

3. Ankle angle: The angle formed between the sole of the foot and a horizontal line passing through the pedal axle. This angle was measured at ATP, 90°, ABP, and 270°.

4. Pronation and Supination: The angle formed between the sole of the shoe and the pedal deck, measured in the frontal plane, posterior view. Pronation occurred when the sole of the shoe rotated laterally; supination occurred when the sole of the shoe rotated medially. Pronation was represented by a postive angle, supination by a negative angle, and the neutral position (no pronation or supination) by an angle of zero.

5. Tibial varus/valgus: The angle formed by the longitudinal axis of the shank with a vertical line passing through the knee joint, measured in the frontal plane, posterior view. Varus occurred when the knee was displaced laterally with respect to the foot. Valgus occurred when the knee was displaced medially to the foot. The neutral position occurred when the knee was directly over the foot. Varus was measured as a positive angle, valgus as a negative angle, and the neutral position was designated as an angle of zero.

6. EMG Area or EMG Impulse: The area under the EMG curve, measured in microvolts times milliseconds. The EMG Area was normalized.

7. Recruitment Order and Time to Peak EMG: Recruitment order was the order in which the muscles reach peak recruitment during the phases of a crank cycle. Time to peak EMG was measured by the time lapsed from the beginning of the crank cycle until peak EMG was achieved.

8. Phase: The angular distance in each quadrant of a crank cycle. Phase 1 was defined as the angular distance between ATP and 90°, Phase 2 was the angular distance between 90° and ABP, Phase 3 was the angular distance between ABP and 270°, and Phase 4 was the angular distance between 270° and ATP.

Equipment

Bicycle Ergometer

All subjects performed the trials on the same bike; the pedals were changed between trials. Trials were performed consecutively so that seat height was identical for all trials. Seat height was set to allow 15° of knee flexion at ABP. The ergometer selected for this study was the Fuid+ Trainer by CycleOps, New York. This unit is capable of delivering up to 1000 watts of resistance. Resistance can be delivered in five levels. The ergometer used fluid to generate resistance. This type of resistance unit provided the rider with smooth resistance throughout the crank cycle. The bike frame was placed in the ergometer such that axle of the rear wheel was centered in the resistance unit. The front tire rested on the floor. All subjects pedaled against the same load. The ergometer was set to Stage 3. The bike used was a 21-speed all-terrain bike. The bike was placed in gear position 11.

Pedal Designs

The flat pedals were lightweight aluminum pedals from Shimano (Shimano American Corporation, Irvine, CA).

The spring-recentered pedals selected for this study were the ATAC pedal by Time (TimeSport America, Santa Barbara, CA). This model used a special cleat design that required the ride to insert the cleat while the ankle was in 0° of ankle flexion. The rider could exit the pedal by externally rotating the heel. The ATAC pedal offered 10° of rotational float and 3 mm of medial-lateral translation with a spring-loaded mechanism which recentered the foot on the pedal.

The float with friction pedals used for this study were model SP-M747 by Shimano. This model used a special cleat design that allowed the rider to insert the cleat at angles of up to 30° of ankle flexion. This design also allowed the rider to alter the amount of force necessary to exit the pedal. The pedals were placed at an equal retention setting for all subjects. This model offered 8° of rotational float and allowed the rider to move the foot upon the pedal against frictional resistance.

Both clipless pedals allow the cleat to be installed to place the tibia in external rotation, internal rotation, or a neutral position. Both designs allow the rider to exit the pedal by externally rotating the heel. Subjects were allowed to use their own cycling shoes, but cleats were set to a neutral position (0° of tibial rotation) for all subjects during the clipless condition.

Metronome

A Pico Club metronome (Seiko, Japan) monitored cadence. This model had audio and visual cadence capabilities. It had a range of 25 to 250 beats per minute (bpm). It was battery operated and credit card size. The metronome was placed in audio mode and held by a researcher near the testing site. Subjects were instructed to pedal in a manner such that they achieved ATP with the right foot at each beat of the metronome.

EMG

The EMG equipment used for this study was a Myosystem 2000, Noraxon, Phoenix, AZ. Peak Motus (Peak Performance Technology, Inc.) was used to synchronize the EMG data with the video data. EMG electrodes used in this study were Medi-Trace Pellet (Graphic Controls Corp., Buffalo, NY) silver-silver chloride disposal.

Peak Motus System

Video data were captured with two Panasonic cameras (Panasonic Industrial Factory Service Center, Secaucus, NJ): (1) a WV-D5100HS, and (2) an AG-450. These cameras with zoom lenses were genlocked.

Panasonic model AG7350 SVHS video recorder attached to a Sony Trinitron, 13" diagonal video monitor was used to transfer sections of the tape to be analyzed by the computer. The software used to capture video images, digitize the motion, smooth the data, and calculate variables was Peak Motus System, Peak Perfomance Technologies, Inc.

CHAPTER IV

RESULTS AND DISCUSSION

Introduction

Lower limb kinematics during cycling can be influenced by equipment, particularly the pedals. Just as a runner's gait can be affected by different shoe designs, a cyclist's pedaling gait can be affected by different pedal designs. Recent innovations in pedal design permit cyclists to secure the feet to the pedals, providing a more stable platform for force transmission between the crank and the lower limb, while allowing foot movement at the pedal. This type of foot-pedal interface allows the cyclist to pedal more efficiently, transferring msuscular force to the crank while reducing constraint loads in the joints of the lower extremity. Subjects pedaled with three different pedal designs at two cadences. Video and EMG data were collected and analyzed to determine differences in lower limb kinematics among the pedals at each cadence.

Results

Trial Consistency

Randomized block factorial ANOVAs were calculated to check for consistency among the five trials for thigh, knee, ankle, inversion/eversion, and tibial varus/valgus angles. The ANOVAs for the thigh, knee, and ankle contained one research variable, trials with five levels. These ANOVAs treated speed and pedal design as blocks or subjects. The ANOVAs for inversion/eversion and varus/valgus contained two research variables: (1) trials, with five levels, or cycles of motion; and (2) phases with two levels, push and pull.

For the clip and flat pedals, no significant differences were found among the five trials for thigh, knee, and ankle angle (see Table 1). A significant difference was found among the five trials for the time pedal for the thigh and knee angles, $F(4, 444) = 2.41$, $p < .05$, and $F(4, 444) = 2.54$, $p < .05$, respectively. However, no significant difference was found for the time pedal for the ankle angle.

No significant difference in inversion/eversion angle ROM was found among the five trials for clip, flat, and time pedals (see Table 2). No significant difference in mean inversion/eversion angle was found between phases for the flat pedal. A significant difference was found between phases for the clip pedal at 60 rpm, $F(1, 217) = 5.19$, $p < .05$. A significant difference between phases was found for the clip and time pedals at 90-rpm, $F(1, 217) = 4.00$, $p < .05$, and $F(1, 217) = 15.54$, $p < .05$, respectively.

No significant difference in maximum or minimum varus/valgus angle was found among the trials for the clip, flat, and time pedals (see Table 3). Significant differences were found between phases for clip, flat, and time pedals at 60 rpm, $F(1, 217) = 470.96$, $p < .05$, $F(1, 217) = 160.33$, $p < .05$, and $F(1, 217) = 346.69$, $p < .05$, respectively. Significant differences were found between phases for clip,

Table 1

ANOVA Summaries for Determining Trial Consistency,
Calculated Across Speeds and Pedals for Angles

Angle	Pedal	Source	SS	df	MS	F
Thigh	Clip	Blocks	125707.60	111	1132.50	244.07*
		Trials	2.23	4	0.56	0.12
		Residual	2062.06	444	4.64	
	Flat	Blocks	125995.30	111	1135.09	1146.56*
		Trials	4.38	4	1.09	1.10
		Residual	440.02	444	0.99	
	Time	Blocks	122865.20	111	1106.89	639.82*
		Trials	16.71	4	4.18	2.41*
		Residual	768.86	444	1.73	
Knee	Clip	Blocks	354155.70	111	3190.59	1131.41*
		Trials	8.30	4	2.07	0.73
		Residual	1251.35	444		
	Flat	Blocks	355446.60	111	3202.22	1442.44*
		Trials	4.01	4	1.00	0.45
		Residual	987.43	444	2.22	
	Time	Blocks	336723.00	111	3033.54	675.62*
		Trials	45.70	4	11.42	2.54*
		Residual	1994.51	444	4.49	
Ankle	Clip	Blocks	67880.90	111	611.54	58.13*
		Trials	29.19	4	7.30	0.69
		Residual	4668.57	444	10.52	
	Flat	Blocks	50970.43	111	459.19	119.27*
		Trials	30.97	4	7.74	2.01
		Residual	1707.11	444	3.85	
	Time	Blocks	57088.21	111	514.31	132.55*
		Trials	11.89	4	2.97	0.76
		Residual	1722.51	444	3.88	

Table 2

ANOVA Summaries for Determining Trial Consistency
for Inversion/Eversion

Pedal	RPM	Source	SS	df	MS	F
Clip	60	Blocks	1099.33	13	84.56	10.47*
		Trials (T)	28.72	4	7.18	0.89
		Phases (P)	41.93	1	41.93	5.19*
		T x P	31.88	4	7.97	0.99
		Residual	945.45	217	8.08	
Clip	90	Blocks	256.03	13	19.69	8.71*
		Trials (T)	5.44	4	1.36	0.60
		Phases (P)	9.05	1	9.05	4.00*
		T x P	22.24	4	5.56	2.46
		Residual	264.14	217	1.22	
Flat	60	Blocks	90.86	13	6.99	6.85*
		Trials (T)	3.24	4	0.81	0.79
		Phases (P)	3.72	1	3.72	3.65
		T x P	0.93	4	0.23	0.23
		Residual	119.56	217	1.02	
Flat	90	Blocks	645.98	13	49.69	2.39*
		Trials (T)	47.23	4	11.81	0.57
		Phases (P)	12.14	1	12.14	0.58
		T x P	105.64	4	26.41	1.29
		Residual	2435.79	217	20.82	
Time	60	Blocks	302.85	13	23.30	15.43*
		Trials (T)	12.01	4	3.00	1.99
		Phases (P)	1.88	1	1.88	1.25
		T x P	4.18	4	1.05	0.70
		Residual	176.90	217	1.51	
Time	90	Blocks	277.14	13	21.32	11.65*
		Trials (T)	0.92	4	0.23	0.13
		Phases (P)	28.44	1	28.44	15.54*
		T x P	5.12	4	1.28	0.70
		Residual	214.09	217	1.83	

Table 3

ANOVA Summaries for Determining Trial Consistency
for Varus/Valgus

Pedal	RPM	Source	SS	df	MS	F
Clip	60	Blocks	3056.87	13	235.14	85.20*
		Trials (T)	11.24	4	2.81	1.02
		Phases (P)	1299.84	1	1299.84	470.96*
		T x P	2.73	4	0.68	0.25
		Residual	323.28	117	2.76	
Clip	90	Blocks	2049.80	13	157.68	14.94*
		Trials (T)	29.19	4	7.30	0.69
		Phases (P)	1047.45	1	1047.45	99.19*
		T x P	15.68	4	3.92	0.37
		Residual	1235.06	117	10.56	
Flat	60	Blocks	2425.39	13	186.57	36.72*
		Trials (T)	2.11	4	0.53	0.10
		Phases (P)	814.48	1	814.48	160.33*
		T x P	10.66	4	2.67	0.53
		Residual	594.11	117	5.08	
Flat	90	Blocks	10606.80	13	815.91	282.32*
		Trials (T)	5.44	4	1.36	0.47
		Phases (P)	343.88	1	343.88	118.99*
		T x P	7.03	4	1.76	0.61
		Residual	338.06	117	2.89	
Time	60	Blocks	1978.26	13	152.17	66.45*
		Trials (T)	5.56	4	1.39	0.61
		Phases (P)	793.92	1	793.92	346.69*
		T x P	3.12	4	0.78	0.34
		Residual	267.90	117	2.29	
Time	90	Blocks	2231.07	13	171.62	58.57*
		Trials (T)	5.78	4	1.44	0.49
		Phases (P)	822.74	1	822.74	280.80*
		T x P	0.51	4	0.13	0.04
		Residual	343.18	117	2.93	

flat, and time pedals at 90-rpm, $F(1, 217) = 99.19$, $p < .05$, $F(1, 217) = 118.99$, $p < .05$, and $F(1, 217) = 280.80$, $p < .05$, respectively.

Research Variables

Video data were analyzed to determine differences in joint angle for the hip, knee, and ankle, for a complete crank cycle. Joint ROM was compared among pedals and between cadences. The dependent variables for joint angles were the mean of the five trials (cycles). A separate ANOVA was calculated for each of the four phases of a complete cycle: (1) ATP, (2) 90°, (3) ABP, and (4) 270°. The ANOVAs consisted of two research variables: (1) pedals with three levels, clip, flat, and time; and (2) rpm with two levels, 60 and 90 revolutions per minute.

Thigh, Knee, and Ankle Angles at ATP

The ANOVA results for the thigh, knee, and ankle angles at the ATP position are presented in Table 4. The results were:

1. No significant difference in thigh angle was found among pedals at ATP, $F(2, 65) = .09$, $p > .05$. The means for the clip, flat, and time pedals were 21.25°, 21.05°, and 21.18°, respectively.

2. No significant difference in knee angle was found among pedals at ATP, $F(2, 65) = 1.68$, $p > .05$. The means for the clip, flat, and time pedals were 71.00°, 71.45°, and 72.02°, respectively.

Table 4

ANOVA Summaries With Main Effects Pedal and RPM
for Angles at ATP

Angle	Source	SS	df	MS	F
Thigh	Subjects	839.72	13	64.59	19.94*
	Pedal (P)	0.57	2	0.28	0.09
	RPM (R)	0.21	1	0.21	0.07
	P x R	3.46	2	1.73	0.53
	Residual	310.80	65	3.25	
Knee	Subjects	1415.00	13	108.85	24.68*
	Pedal (P)	14.83	2	7.42	1.68
	RPM (R)	0.00	1	0.00	0.00
	P x R	17.33	2	8.67	1.97
	Residual	286.59	65	4.41	
Ankle	Subjects	3612.53	13	277.89	15.11*
	Pedal (P)	92.57	2	46.29	2.52
	RPM (R)	12.83	1	12.83	0.70
	P x R	12.52	2	6.26	0.34
	Residual	1195.27	65	18.39	

3. No significant difference in ankle angle was found among pedals at ATP, $F(2, 65) = 2.52$, $p > .05$. The means for the clip, flat, and time pedals were 109.39°, 109.86°, and 111.82°, respectively.

4. No significant difference in thigh angle was found between cadences at ATP, $F(1, 65) = 0.07$, $p > 0.05$. The means for the 60-rpm and 90-rpm were 21.21° and 21.11°, respectively.

5. No significant difference in knee angle was found between cadences at ATP, $F(1, 65) = 0.00$, $p > .05$. The means for the 60-rpm and 90-rpm were 71.49° and 71.49°, respectively.

6. No significant difference in mean ankle angle was found between cadences at ATP, $F(1, 65) = 0.70$, $p > .05$. The means for the 60-rpm and 90-rpm were 110.75° and 109.97°, respectively.

7. For the thigh, knee, and the ankle, the interaction effects, pedal by rpm, were not significant.

Ankle, Knee, and Ankle Angles for the 90° Position

The ANOVA results for the thigh, knee, and ankle angles at 90° of the crank cycle are presented in Table 5. The results were:

1. No significant difference in thigh angle was found among pedals at the 90° position, $F(2, 65) = 0.23$, $p > 0.05$. The means for the clip, flat, and time pedals were 33.66°, 33.29°, and 33.97°, respectively.

2. No significant difference in knee angle was found among pedals at the 90° position, $F(2, 65) = 0.52$, $p < 0.05$. The means for the clip, flat, and time pedals were 110.26°, 107.92°, and 111.32°, respectively.

3. A significant difference in ankle angle was found among pedals at the 90° position, $F(2, 65) = 4.64$, $p < 0.05$. The means for the clip, flat, and time pedals were 116.22°, 115.68°, and 118.45°, respectively. A Tukey HSD test was calculated

Table 5

ANOVA Summaries With Main Effects Pedal and RPM
for Angles at 90°

Angle	Source	SS	df	MS	F
Thigh	Subjects	1533.44	13	117.96	8.46*
	Pedal (P)	6.45	2	3.22	0.23
	RPM (R)	13.50	1	13.50	0.97
	P x R	25.55	2	12.77	0.92
	Residual	906.03	65	13.94	
Knee	Subjects	3589.29	13	276.10	1.71
	Pedal (P)	169.37	2	84.69	0.52
	RPM (R)	136.59	1	136.59	0.84
	P x R	249.23	2	124.62	0.77
	Residual	10519.42	65	161.84	
Ankle	Subjects	3822.00	13	294.00	22.55*
	Pedal (P)	121.05	2	60.52	4.64*
	RPM (R)	51.04	1	51.04	3.91
	P x R	11.20	2	5.60	0.43
	Residual	847.92	65	13.04	

to determine which of the pairwise comparisons of pedals were significant. The results indicated a significant difference between the flat and time pedal. All other pairwise comparisons were not significant.

4. No significant difference in thigh angle was found between cadences at the 90° position, $F(1, 65) = 0.92$, $p > 0.05$. The means for the 60-rpm and 90-rpm cadences were 34.04° and 33.24°, respectively.

5. No significant difference in knee angle was found between cadences at the 90° position, $F(1, 65) = 0.84$, $p > 0.05$. The means for the 60-rpm and 90-rpm cadences were 108.56° and 111.11°, respectively.

6. No significant difference in ankle angle was found between cadences at the 90° position, $F(1, 65) = 3.91$, $p > 0.05$. The means for the 60-rpm and 90-rpm cadences were 116.00° and 117.56°, respectively.

7. For the thigh, knee, and the ankle, the interaction effects pedal by rpm were not significant.

Thigh, Knee, and Ankle Angles for ABP

The ANOVA results for the thigh, knee, and ankle angles at the ABP position of the crank cycle are presented in Table 6. The results were:

1. No significant difference in thigh angle was found among pedals at the ABP position, $F(2, 65)= 1.63$, $p > 0.05$. The means for the clip, flat, and time pedals were 60.12°, 60.15°, and 57.40°, respectively.

2. No significant difference in knee angle was found among pedals at the ABP position, $F(2, 65) = 0.80$, $p > 0.05$. The means for the clip, flat, and time pedals were 137.25°, 137.12°, and 136.37°, respectively.

3. No significant difference in ankle angle was found among pedals at the ABP position, $F(2, 65) = 1.35$, $p > 0.05$. The means for the clip, flat, and time pedals were 129.38°, 128.29°, and 129.63°, respectively.

Table 6

ANOVA Summaries With Main Effects Pedal and RPM for Angles at ABP

Angle	Source	SS	df	MS	F
Thigh	Subjects	1659.29	13	127.64	2.96*
	Pedal (P)	140.34	2	70.17	1.63
	RPM (R)	34.04	1	34.01	0.79
	P x R	113.16	2	56.58	1.31
	Residual	2799.51	65	43.07	
Knee	Subjects	3491.78	13	268.60	34.13*
	Pedal (P)	12.67	2	6.33	0.80
	RPM (R)	1.90	1	1.90	0.24
	P x R	2.04	2	1.02	0.13
	Residual	511.33	65	7.87	
Ankle	Subjects	3700.55	13	284.66	27.21*
	Pedal (P)	28.27	2	14.14	1.35
	RPM (R)	96.36	1	96.36	9.21*
	P x R	27.82	2	13.91	1.33
	Residual	679.67	65	10.46	

4. No significant difference in thigh angle was found between cadences at the ABP position, $\underline{F}(1, 65) = 0.79$, $\underline{p} > 0.05$. The means for the 60-rpm and 90-rpm cadences were 58.59° and 59.86°, respectively.

5. No significant difference in knee angle was found between cadences at the ABP position, $\underline{F}(1, 65) = 0.24$, $\underline{p} > 0.05$. The means for the 60-rpm and 90-rpm cadences were 137.06° and 136.76°, respectively.

6. A significant difference in ankle angle was found between cadences at the ABP position, $F(1, 65) = 9.21$, $p < 0.05$. The mean for the 60-rpm cadence, 128.03°, was smaller than for the 90-rpm cadence, 130.17°.

7. For the thigh, knee, and ankle, the interaction effect pedal by cadence was not significant.

Thigh, Knee, and Ankle Angles for the 270° Position

The ANOVA results for the thigh, knee, and ankle angles at the 270° crank position are presented in Table 7. The results were:

1. No significant difference in thigh angle was found among pedals at the 270° position, $F(2, 65) = 0.66$, $p > 0.05$. The means for the clip, flat, and time pedals were 45.39°, 45.25°, and 45.74°, respectively.

2. No significant difference in knee angle was found among pedals at the 270° position, $F(2, 65) = 2.36$, $p > 0.05$. The means for the clip, flat, and time pedals were 89.79°, 90.22°, and 91.15°, respectively.

3. No significant difference in ankle angle was found among pedals at the 270° position, $F(2, 65) = 2.47$, $p > 0.05$. The means for the clip, flat, and time pedals were 120.89°, 119.64°, and 121.96°, respectively.

4. A significant difference in thigh angle was found between cadences at the 270° position, $F(1, 65) = 20.39$, $p < 0.05$. The mean for the 60-rpm cadence, 46.28°, was greater than for the 90-rpm cadence, 44.64°.

Table 7

ANOVA Summaries With Main Effects Pedal and RPM for Angles at 270°

Angle	Source	SS	df	MS	F
Thigh	Subjects	1260.12	13	96.93	35.12*
	Pedal (P)	3.64	2	1.82	0.66
	RPM (R)	56.29	1	56.29	20.39*
	P x R	6.10	2	3.05	1.11
	Residual	179.42	65	2.76	
Knee	Subjects	1396.17	13	107.40	18.71*
	Pedal (P)	27.04	2	13.52	2.36
	RPM (R)	15.49	1	15.49	2.70
	P x R	3.82	2	1.91	0.33
	Residual	372.83	65	5.74	
Ankle	Subjects	4918.35	13	378.33	24.74*
	Pedal (P)	75.46	2	37.73	2.47
	RPM (R)	118.17	1	118.17	7.73*
	P x R	5.10	2	2.55	0.17
	Residual	993.58	65	15.29	

5. No significant difference in knee angle was found between cadences at the 270° position, $F(1, 65) = 2.70$, $p > 0.05$. The means for the 60-rpm and 90-rpm cadences were 90.82° and 89.96°, respectively.

6. A significant difference in ankle angle was found between cadences at the 270° position, $F(1, 65) = 7.73$, $p < 0.05$. The mean for the 60-rpm cadence, 119.63°, was smaller than for the 90-rpm cadence, 122.00°.

7. For the thigh, knee, and ankle, the interaction effects pedals by cadence were not significant.

Inversion/Eversion Angle

An ANOVA for inversion/eversion angle, with research variables pedal design, cadence, and cycle phase, were calculated. The results of the ANOVA are presented in Table 8. The results for inversion/eversion were:

1. No significant difference in inversion/eversion were found among the pedals, $F(2, 143) = 0.06$, $p > .05$. The means for the clip, flat, and time pedals were 3.65°, 3.71°, and 3.58°, respectively.

Table 8

ANOVA Summaries With Main Effects Pedal, RPM, and Phase for Inversion/Eversion

Source	SS	df	MS	F
Blocks	174.25	13	13.40	3.92*
Pedal (P)	0.44	2	0.22	0.06
Phase (S)	0.90	1	0.09	0.03
RPM (R)	8.32	1	8.32	2.43
P x S	5.85	2	2.92	0.85
P x R	17.84	2	8.92	2.61
S x R	2.15	1	2.15	0.63
P x S x R	11.34	2	5.67	1.66
Residual	489.73	143	3.42	

2. No significant difference in inversion/eversion was found between the two phases, $F(1, 143) = 0.03$, $p > 0.05$. The means of the push and pull phases were 3.67° and 3.62°, respectively.

3. No significant difference in inversion/eversion was found between cadences, $F(1, 143) = 2.43$, $p > 0.05$. The means for the 60-rpm and 90-rpm cadences were 3.42° and 3.87°, respectively.

4. No significant first or second order interaction effects were found.

Varus/Valgus Angle

An ANOVA for the varus/valgus angle, with research variables pedal design, cadence, and cycle phase, were calculated. An ANOVA summary is presented in Table 9. The results for varus/valgus were:

1. A significant difference in the varus/valgus angle was found among the pedals, $F(2, 143) = 3.28$, $p < .05$. The means for the clip, flat, and time pedals were 34.67°, 32.73°, and 33.69°, respectively. Results of the Tukey HSD multiple comparison test revealed a significant difference between the flat and clip pedals.

2. A significant difference in the varus/valgus angle was found between phases, $F(1, 143) = 62.34$, $p < .05$. The means for the push and pull phases were 31.26° and 36.13°, respectively.

3. A significant difference in the varus/valgus angle was found between cadences, $F(1, 143) = 4.17$, $p < .05$. The means for the 60-rpm and 90-rpm cadences were 34.33° and 33.07°, respectively.

4. No significant first or second order interaction effects were found.

Table 9

ANOVA Summaries With Main Effects Pedal, RPM, and Phase for Valgus/Varus

Source	SS	df	MS	F
Blocks	2441.11	13	187.78	11.73*
Pedal (P)	105.17	2	52.59	3.28*
Phase (S)	998.01	1	998.01	62.34*
RPM (R)	66.81	1	66.81	4.17*
P x S	21.44	2	10.72	0.67
P x R	32.48	2	16.24	1.01
S x R	5.21	1	5.21	0.33
P x S x R	4.86	2	2.43	0.15
Residual	2289.49	143	16.01	

EMG Area

Randomized block factorial ANOVAs were calculated to check for significant differences in EMG area for the three pedals, two cadences, and four phases of a crank cycle. The phases were; (1) Phase 1, the angular distance between ATP and 90° of a complete crank cycle; (2) Phase 2, the angular distance between 90° and ABP; (3) Phase 3, the angular distance between ABP and 270°; and

(4) Phase 4, the angular distance between 270° and ATP. ANOVAs were calculated for the rectus femoris, vastus lateralis, vastus medialis, medial hamstrings, biceps femoris, gastrocnemius, anterior tibialis muscles.

Rectus Femoris

The ANOVA summary for the rectus femoris is presented in Table 10. The results were:

1. No significant difference in EMG area was found among pedals for the rectus femoris muscle, $F(2, 253) = 0.33$, $p > .05$. The means for the clip, flat, and time pedals were 141.51 μv·s, 141.07 μv·s, and 135.18 μv·s, respectively.

2. No significant difference in EMG area was found between cadences for the rectus femoris muscle, $F(1, 253) = 2.44$, $p > .05$. The means for the 60-rpm and 90-rpm cadences were 133.66 μv·s and 144.84 μv·s, respectively.

3. A significant difference in EMG area was found among the phases for the rectus femoris muscle, $F(3, 253) = 35.94$, $p < .05$. The means for Phase 1, 2, 3, and 4 were 193.15 μv·s, 111.83 μv·s, 98.60 μv·s, and 153.45 μv·s, respectively. The Tukey HSD multiple comparison test was run to determine significant differences between pairs of phases. Differences existed between: (a) Phase 3 and 4, (b) Phase 1 and 3, (c) Phase 2 and 4, (d) Phase 1 and 2, and (e) Phase 1 and 4.

4. No significant first- or second-order interaction effects were found for the rectus femoris.

Table 10

ANOVA Summary for EMG Area of Rectus Femoris Muscle

Source	SS	df	MS	F
Subject	49041.51	11	4458.32	1.21
Pedal (P)	2396.84	2	1198.42	0.33
Cadence (C)	8997.55	1	8997.55	2.44
Phase (S)	396843.10	3	132281.00	35.94*
P x C	881.17	2	440.59	0.12
P x S	13026.89	6	2171.15	0.59
C x S	27516.57	3	9052.19	2.46
P x C x S	12925.05	6	2154.18	0.59
Residual	931246.79	253	3680.82	

*Significant at the .05 level.

Vastus Lateralis

The ANOVA summary for the vastus lateralis is presented in Table 11. The results were:

1. No significant difference in EMG area for the vastus lateralis was found among pedals, $F(2, 253) = 1.87$, $p > .05$. The means for the clip, flat, and time pedals were 84.77 µv·s, 88.73 µv·s, and 94.63 µv·s, respectively.

Table 11

ANOVA Summary for EMG Area of Vastus Lateralis Muscle

Source	SS	df	MS	F
Subject	24049.42	11	2186.31	3.59*
Pedal (P)	2280.92	2	1140.46	1.87
Cadence (C)	8622.80	1	8622.80	14.17*
Phase (S)	18657.86	3	6219.29	10.22*
P x C	107.65	2	53.83	0.09
P x S	1158.65	6	193.11	0.32
C x S	2574.78	3	858.26	1.41
P x C x S	1756.80	6	292.80	0.48
Residual	153952.61	253	608.51	

*Significant at the .05 level.

2. A significant difference in EMG area for the vastus lateralis was found between cadences, $F(1, 253) = 14.17$, $p < .05$. The means for the 60-rpm and 90-rpm cadences were 98.18 μv·s and 87.24 μv·s, respectively.

3. A significant difference in EMG area for the vastus lateralis was found among phases, $F(3, 253) = 10.22$, $p < .05$. The means for Phase 1, 2, 3, and 4 were 97.23 μv·s, 81.43 μv·s, 89.42 μv·s, and 102.75 μv·s, respectively. The Tukey HSD multiple comparison test indicated significant differences between the following pairs of means: (a) Phase 1 and 2, (b) Phase 2 and 4, and (c) Phase 3 and 4.

4. No significant first- or second-order interaction effects were found for the vastus lateralis.

Vastus Medialis

The ANOVA summary for the vastus medialis is presented in Table 12. The results were:

Table 12

ANOVA Summary for EMG Area of Vastus Medialis Muscle

Source	SS	df	MS	F
Subject	63448.37	11	5768.03	5.22*
Pedal (P)	50.59	2	25.30	0.02
Cadence (C)	5.48	1	5.48	0.01
Phase (S)	138705.01	3	46235.03	41.85*
P x C	114.97	2	57.48	0.05
P x S	3069.91	6	511.65	0.46
C x S	8317.75	3	2772.58	2.51*
P x C x S	3681.04	6	613.51	0.56
Residual	279521.59	253	1104.83	

*Significant at the .05 level.

1. No significant difference in EMG area for the vastus medialis was found among pedals, F(2, 253) = 0.02, p > .05. The means for the clip, flat, and time pedals were 115.17 µv·s, 114.75 µv·s, and 115.77 µv·s, respectively.

2. No significant difference in EMG area for the vastus medialis was found between cadences, F(1, 253) = 0.01, p > .05. The means for the 60-rpm and 90-rpm cadences were 115.45 µv·s and 115.09 µv·s, respectively.

3. A significant difference in EMG area for the vastus medialis was found among phases, F(3, 253) = 41.85, p > .05. The means for Phase 1, 2, 3, and 4 were 144.16 µv·s, 96.00 µv·s, 92.04 µv·s, and 128.72 µv·s, respectively. The Tukey HSD test for multiple comparisons indicated significant differences between the following pairs: (a) Phase 3 and 4, (b) Phase 1 and 3, (c) Phase 2 and 4, and (d) Phase 1 and 4.

4. No significant first-or second-order interaction effects were found.

Medial Hamstrings

The ANOVA summary for the medial hamstrings is presented in Table 13. The results were:

1. No significant difference in EMG area for the medial hamstrings was found between pedals, F(2, 253) = 0.30, p > .05. The means for the clip, flat, and time pedal were 107.63 µv·s, 104.86 µv·s, and 105.00 µv·s, respectively.

2. A significant difference in EMG area for the medial hamstrings was found between cadences, F(1, 253) = 4.25, p > .05. The means for the 60-rpm and 90-rpm cadences were 116.72 µv·s and 102.42 µv·s, respectively.

Table 13

ANOVA Summary for EMG Area of Medial Hamstring Muscle

Source	SS	df	MS	F
Subject	66021.13	11	6001.92	7.64*
Pedal (P)	468.41	2	234.21	0.30
Cadence (C)	3340.17	1	3340.17	4.25*
Phase (S)	82724.65	3	27574.88	35.09*
P x C	1863.34	2	931.67	1.19
P x S	2271.25	6	378.54	0.48
C x S	1984.68	3	661.56	0.84
P x C x S	2277.97	6	379.66	0.48
Residual	198821.26	253	785.86	

*Significant at the .05 level.

3. A significant difference in EMG area for the medial hamstrings was found among phases, $F(3, 253) = 35.09$, $p < .05$. The means for Phases 1, 2, 3, and 4 were 102.37 μv·s, 133.41 μv·s, 100.30 μv·s, and 87.24 μv·s, respectively. The Tukey HSD test indicated significant differences between the following pairs of phases: (a) Phase 1 and 4, (b) Phase 2 and 4, (c) Phase 2 and 3, and (d) Phase 1 and 2.

4. No significant first- or second-order interaction effects were found for the medial hamstrings.

Biceps Femoris

The ANOVA summary for the biceps femoris is presented in Table 14. The results were:

Table 14

ANOVA Summary for EMG Area of Biceps Femoris Muscle

Source	SS	df	MS	F
Subject	65817.29	11	5983.39	3.63*
Pedal (P)	1557.90	2	778.95	0.47
Cadence (C)	2055.74	1	2055.74	1.25
Phase (S)	211445.20	3	70481.73	42.76*
P x C	705.14	2	352.57	0.21
P x S	4708.76	6	784.79	0.48
C x S	11239.76	3	3746.59	2.27
P x C x S	7756.64	6	1292.77	0.78
Residual	417030.97	253	1648.34	

*Significant at the .05 level.

1. No significant difference in EMG area was found among pedals for the biceps femoris, $F(2, 253) = 0.47$, $p > .05$. The means for the clip, flat, and time pedals were 128.17 µv·s, 123.04 µv·s, and 123.47 µv·s, respectively.

2. No significant difference in EMG area was found between cadences for the biceps femoris, $\underline{F}(1, 253) = 1.25$, $\underline{p} > .05$. The means for the 60-rpm and 90-rpm cadences were 127.56 μv·s and 122.22 μv·s, respectively.

3. A significant difference in EMG area was found among phases for the biceps femoris, $\underline{F}(3, 253) = 42.76$, $\underline{p} > .05$. The means for Phase 1, 2, 3, and 4 were 126.30 μv·s, 168.43 μv·s, 105.89 μv·s, and 98.86 μv·s, respectively. The Tukey HSD test indicated significant differences between the following pairs of phases: (a) Phase 1 and 4, (b) Phase 2 and 4, (c) Phase 1 and 3, (d) Phase 2 and 3, and (e) Phase 1 and 2.

4. No significant first- or second-order interaction effects were found for the biceps femoris.

Gastrocnemius

The ANOVA summary for the gastrocnemius is presented in Table 15. The results were:

1. No significant difference in EMG area was found between pedals for the gastrocnemius, $\underline{F}(2, 253) = 1.27$, $\underline{p} > .05$. The means for the clip, flat, and time pedals were 96.97 μv·s, 90.56 μv·s, and 91.73 μv·s, respectively.

2. A significant difference in EMG area was found between cadences for the gastrocnemius, $\underline{F}(1, 253) = 16.99$, $\underline{p} < .05$. The means for the 60-rpm and 90-rpm cadences were 85.87 μv·s and 100.30 μv·s, respectively.

Table 15

ANOVA Summary for EMG Area of Gastrocnemius Muscle

Source	SS	df	MS	F
Subject	162173.20	11	14743.02	16.70*
Pedal (P)	2238.48	2	1119.24	1.27
Cadence (C)	14998.11	1	14998.11	16.99*
Phase (S)	36976.61	3	12325.54	13.97*
P x C	1152.81	2	576.41	0.65
P x S	776.31	6	129.39	0.15
C x S	9478.86	3	3159.62	3.58*
P x C x S	2494.21	6	415.00	0.47
Residual	223297.94	253	882.60	

*Significant at the .05 level.

3. A significant difference in EMG area was found among the phases for the gastrocnemius, $F(3, 253)=13.97$, $p < .05$. The means for Phases 1, 2, 3, and 4 were 74.63 μv·s, 92.96 μv·s, 101.88 μv·s, and 102.87 μv·s, respectively.

4. A significant first order interaction, cadence by phase was found, $F(3, 253) = 3.58$, $p < .05$. A graph (see Figure 1) of the means for the phases and the cadences indicated similar responses at Phases 1 and 4. However, at Phases 2 and 3

the gastrocnemius muscle's EMG area was greater for the 90-rpm cadence compared to the 60-rpm cadence.

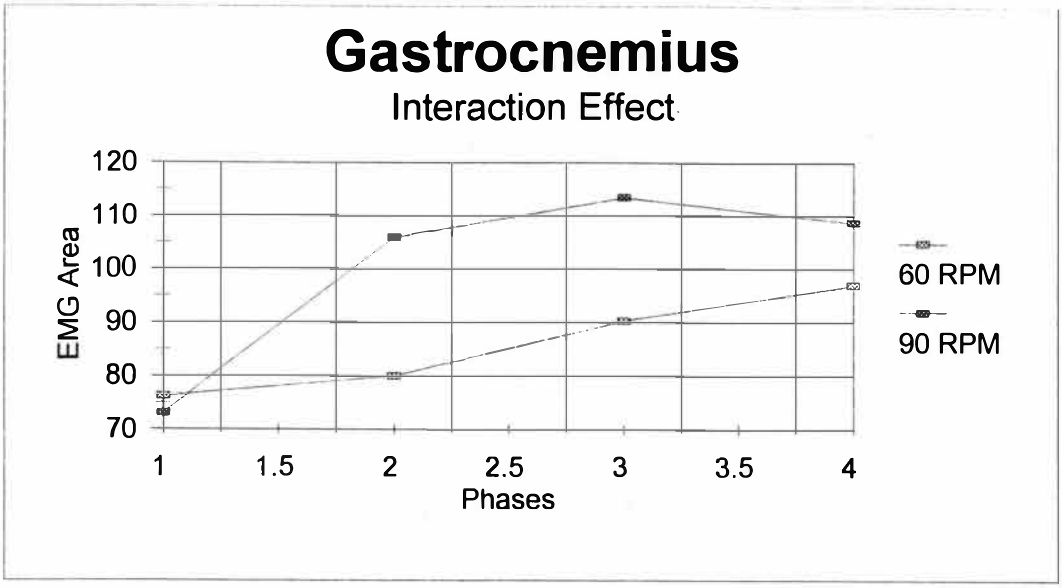

Figure 1. Gastrocnemius Interaction Effect for Phase by Cadence.

Anterior Tibialis

The ANOVA summary for the anterior tibialis is presented in Table 16. The results were:

1. No significant difference in EMG area was found among pedals for the anterior tibialis, $\underline{F}(2, 253) = 0.72$, $\underline{p} > .05$. The means for the clip, flat, and time pedals were 140.48 µv·s, 138.12 µv·s, and 133.83 µv·s, respectively.

2. No significant difference in EMG area was found between cadences for the anterior tibialis, $\underline{F}(1, 253) = 0.40$, $\underline{p} > .05$. The means for the 60-rpm and 90-rpm cadences were 138.92 µv·s and 136.03 µv·s, respectively.

Table 16

ANOVA Summary for EMG Area of Anterior Tibialis Muscle

Source	SS	df	MS	F
Subject	157522.10	11	14320.19	9.46*
Pedal (P)	2177.12	2	1088.56	0.72
Cadence (C)	601.35	1	601.35	0.40
Phase (S)	300414.20	3	100138.10	66.17*
P x C	3515.94	2	1756.97	1.16
P x S	11081.29	6	1846.88	1.22
C x S	3252.21	3	1084.07	0.72
P x C x S	20270.78	6	3378.46	2.23*
Residual	382861.55	253	1513.29	

*Significant at the .05 level.

3. A significant difference in EMG area was found among phases for the anterior tibialis, $F(3, 253) = 66.17$, $p > .05$. The means for Phase 1, 2, 3, and 4 were 144.55 µv·s, 185.58 µv·s, 121.95 µv·s, and 97.93 µv·s, respectively.

4. The second-order interaction, pedal by cadence by phase, was significant, $F(6, 253) = 2.23$, $p < .05$. For both cadences, Phase 2 was greater than Phase 1, Phase 1 was greater than Phase 3, and Phase 3 was greater than Phase 4 (Figure 2). This same pattern occurred for pedals and phases (Figure 3). For cadence and

pedals (Figure 4) 90-rpm cadence produces a greater EMG area than the 60-rpm cadence for the clip and flat pedals and the clip pedal had a greater EMG area than the flat pedal for both cadences. However, the patterns produced by the time pedal for both cadences were different from the patterns of the clip and flat pedals. For the time pedal, the 60-rpm cadence had a greater EMG area than the 90-rpm cadence.

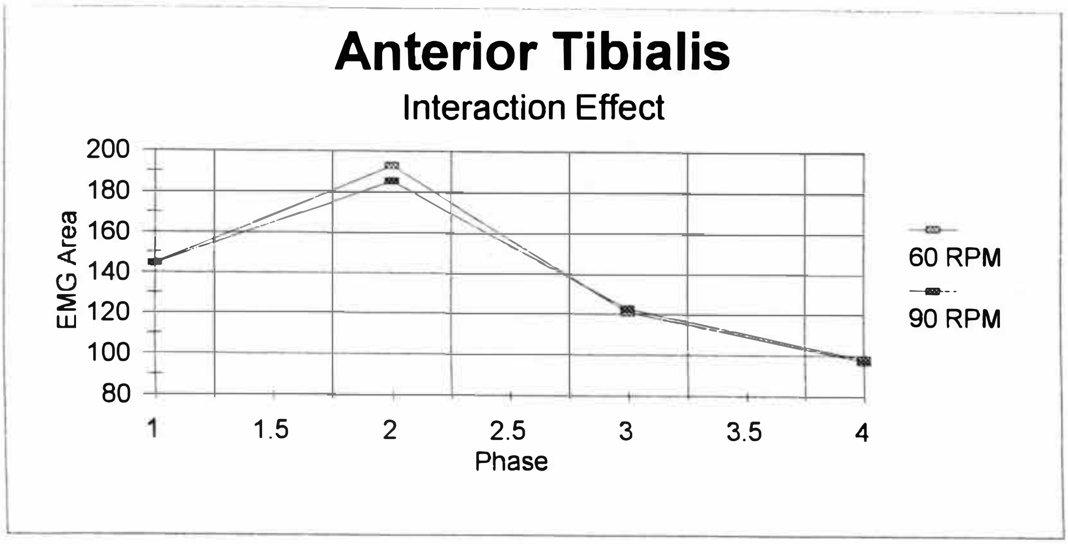

Figure 2. Anterior Tibialis Interaction Effect for Phase by Cadence.

Discussion

The purpose of this study was to investigate the EMG response of selected muscles in the lower extremities during the mountain bike pedaling motion. The EMG areas of six muscles were measured across pedals (clip, flat, and time), cadence (60- and 90-rpm), and phases of a complete cycle. A complete cycle of the motion was divided into four quadrants, each representing 90° of one complete

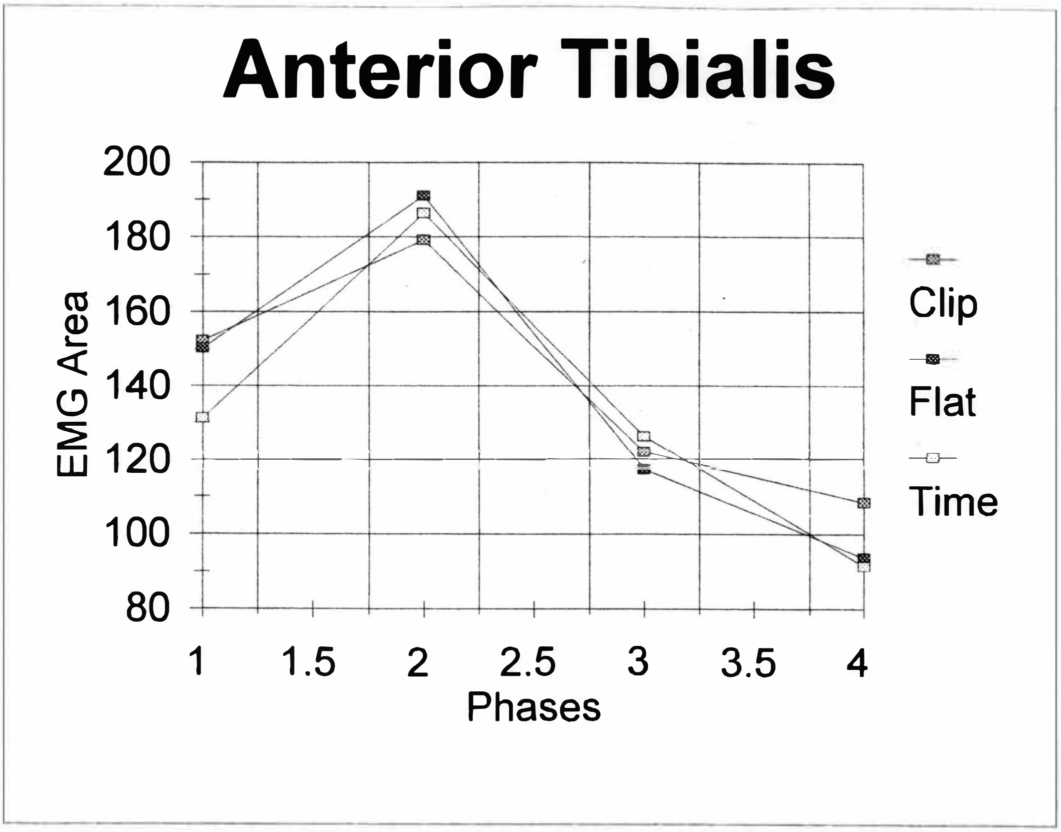

Figure 3. Anterior Tibialis Interaction Effect for Pedal by Phase.

revolution of the crank, starting at the ATP position. The phases will be referred to as the first, second, third, and fourth quadrants. The scope of this study included data collected across five trials, using three pedals, and two cadences. To support and explain the EMG results, angular kinematics of the lower extremities were also measured. The discussion is divided into the following areas: (a) trial consistency, (b) hip extension, (c) hip flexion, (d) knee extension, (e) knee flexion, (f) ankle plantar flexion, and (g) ankle dorsiflexion.

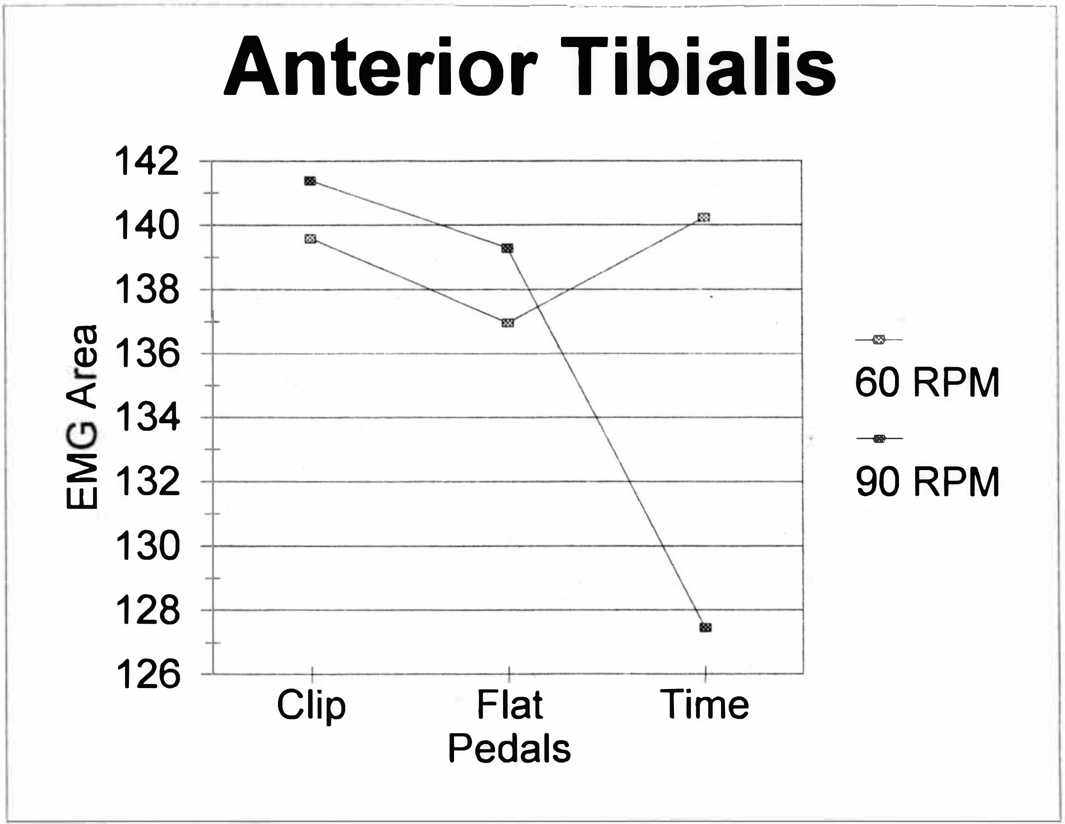

Figure 4. Anterior Tibialis Interaction Effect for Cadence by Pedal.

Trial Consistency

The first data analysis focused on kinematic trial consistency. Subjects' angular motion of the lower extremity was consistent across the trials except for the time pedal condition. The ankle and knee angles for the time pedal were not consistent. This was a new pedal, just placed on the market, with which subjects were unfamiliar. Variations in the design of each pedal may have contributed to the observed differences. The primary differences in design between clip and time pedals were the amount of float allowed and the type of float allowed.

Each pedal offered a different amount of float. The clip pedals offered 8° of rotational float between the foot and pedal. The time pedals offered 10° of rotational float between the foot and the pedal. The amount of rotational float offered by a pedal can affect joint angles in the lower extremity. Each pedal offered a different type of float. The clip pedals offered float with friction. This type of float inhibits rotational motion between the foot and pedal. The rider can reposition the foot within the rotational range, but the foot does not move freely on its own. The time pedals offered spring-recentered float. This design features a spring, which returns the foot to a center point in the rotational range. The center point can be adjusted by the positioning of the cleat on the shoe. If the foot is able to move freely through the rotational range, lower extremity joint angles would be affected. When foot movement is inhibited, joint angles could be affected and joint loads could be increased, resulting in an increased likelihood of injury.

Hip Extension

The EMG data for the hip extensor, MH, indicated that no differences existed among the three pedals. Therefore, pedal design was not a factor in the recruitment of hip extensor muscles during a crank cycle.

A significant difference in EMG area for MH was present between cadences. The 60-rpm cadence recruited the muscle to a greater extent than the 90-rpm cadence. We had expected EMG to increase linearly with cadence. These findings are probably the result of significant differences between the cadences for ankle motion at ABP and varus/valgus motion of the lower extremity. The ankle was more plantar flexed at ABP for the 90-rpm cadence than for the 60-rpm cadence. This difference in ankle angle may have been a result of the greater torque that was required to maintain the higher cadence. MH was recruited to a greater extent to produce torque at the lower cadence. The 60-rpm cadence had a greater varus/valgus angle than the 90-rpm cadence. MH produced this medial thigh movement. This motion aligns the knee over the foot/ankle producing greater torque.

For MH, significant differences were present among phases. MH was recruited to a greater extent during the push phase (concentric). EMG area for MH peaked during Phase 2. During Phase1 and Phase 2, MH extends the hip and assists in medial thigh movement. EMG data for Phase 1 and Phase 3 were similar. During Phase 3, MH produces knee flexion. Varus/valgus angles were smaller during the push-down phase of the crank cycle. This places the knee closer to the foot/ankle, producing more torque during the push phase.

Hip Flexion

The EMG area of the hip flexor, RF, indicated no differences existed among the pedals. Pedal design was not a factor in the recruitment of this muscle during a crank cycle.

No significant differences were found between cadences for RF. We had expected EMG area to increase with cadence. Cadence did not influence the recruitment of RF during a crank cycle.

EMG data did indicate significant differences between phases. The data indicate that RF was most active between 270° and 90°, or over the top half of a crank cycle. These findings indicate that RF is active as a hip flexor and a knee extensor during a crank cycle. During Phase 4, RF flexes the hip, allowing the pedal to pass ATP. RF recruitment is significantly greater during Phases 1 and 4 than during Phases 2 and 3. RF becomes a knee extensor during Phase 1.

Knee Extension

The EMG area of three knee extensor muscles, vastus lateralis, vastus medialis, and rectus femoris indicated no differences existed among the three pedals. Therefore, pedals were not a factor in the recruitment of these muscles during a crank cycle.

For the three knee extensor muscles, only the vastus lateralis muscle indicated a significant difference between the cadences. The 60-rpm cadence recruited the muscle to a greater degree than the 90-rpm cadence. It would be logical to expect more muscle recruitment to move a limb at a faster cadence. Also, this result was probably related to the significant differences found between the cadences for ankle motion at ABP and the varus/valgus motion of the lower extremity. The ankle was more plantar flexed at ABP for the 90-rpm cadence than for the 60-rpm cadence. This difference may have been a result of the greater torque that was required to maintain the higher cadence. The 60-rpm cadence had a greater varus-valgus angle than the 90-rpm cadence. The knee was closer to being over the ankle/foot during the 90-rpm cadence. More torque would be required to pedal at the faster cadence. One way of producing more torque would be to align the knee over the ankle/foot, which is what occurred during the 90-rpm cadence. The results indicate that when more torque is needed to maintain a higher cadence, the varus/ valgus angle was smaller. When the varus/valgus angle places the knee lateral to the foot, a greater muscle recruitment would be expected in the vasts lateralis than in the vastus medialis or restus femoris.

All three muscles indicated significant differences among the phases. The vastus medialis and rectus femoris showed a similar pattern of differences among the phases. Both showed greatest recruitment in the first quadrant (concentric motion). The second greatest recuitment occurred during the fourth quadrant (final part of eccentric motion). Equal recruitment occurred during the second and third quadrants for the rectus femoris and vastus medialis muscles. The vastus lateralis' greater recruitment occurred during the fourth quadrant (eccentric motion) and the first quadrant (concentric motion). Recruitment during the second and third quadrants were not different but were smaller than the first and fourth quadrants. A possible reason that the vastus lateralis' EMG area was different from the other knee extensor muscles could be due to the significant difference found for the varus/ valgus angle between the push-down and the pull-up phases. A greater degree of lateral rotation (varus/valgus) occurred during the pull-up phase (concentric motion) than during the push-down phase (eccentric motion). Thus, the lateral side of the lower extremity would be strong and tight, while the medial side would be stretched and weak due to the position of the knee. This would be similar to the muscle imbalance found between the medial and lateral sides of the lower extremities of people who have genu varum.

Knee Flexion

The EMG area of the knee flexor muscles, MH, BF, and GAS, indicated no significant differences existed among the pedals. Pedal design was not a factor in the recruitment of these muscles during a crank cycle.

EMG data indicated that significant differences were present between cadences for MH, BF, and GAS. MH and BF were significantly greater at 60-rpm than at 90-rpm, but GAS was significantly greater at 90-rpm than at 60-rpm. EMG data for MH and BF are similar to VL, and also may be attributed to differences in ankle angle at ABP and varus/valgus motion of the lower extremity. GAS results maybe due to greater forces transferred between the pedal and lower extremity at the faster cadence. The knee was more lateral to the foot for the 60-rpm cadence, than for the 90-rpm cadence. BF assists in lateral rotation of the thigh, and greater muscle recruitment would be expected in BF. Because BF is assisting in lateral movement of the thigh, MH is recruited to a greater extent to produce knee flexion.

GAS may also be recruited to a greater extent to produce knee flexion at the faster cadence.

Each of the muscles indicated significant differences among the phases. MH and BF showed a similar pattern of differences. Both MH and BF showed their greatest recruitment during the second quadrant. During this phase, MH was assisting with hip extension (eccentric) and varus/valgus motion (eccentric). Near ABP, BF and GAS initiate knee flexion (eccentric). The second largest recruitment for both MH and BF occurred during the first quadrant, where MH was an active hip extensor (eccentric). Quadrants 3 and 4 produced the least muscle recruitment for MH and BF. For BF and MH, recruitment was significantly greater during the push-down phase than during the pull-up phase.

Ankle Plantar Flexion

The EMG area of the GAS indicated no significant differences among pedals. Therefore, pedals did not influence the recruitment of this muscle.

The EMG data indicate significant differences in GAS recruitment were present between cadences. GAS was recruited to a greater extent at 90-rpm than at 60-rpm. This would seem logical, as greater muscle recruitment would be expected when pedaling at a higher cadence. The ankle was significantly more plantar flexed at ABP and 270° at 90-rpm than at 60-rpm. The ankle also traveled through a greater ROM at 90-rpm than at 60-rpm. A possible reason for this could be that varus/valgus angle was less at 90-rpm than 60-rpm, so the knee was in closer alignment over the ankle/foot. This would produce greater torque to help maintain the higher cadence.

The EMG data did indicate significant differences among phases for the GAS. The ankle is plantar flexed throughout the crank cycle, reaching the greatest degree of plantar flexion near ABP. The greatest amount of GAS recruitment occurred during Quadrant 4. GAS recruitment in Quadrant 3 is nearly as great as during Quadrant 4. During the pull phase, ankle plantar flexion is significantly greater than during push phase. GAS activity begins to increase significantly during Quadrant 2, when forces generated by the limb reach their peak. Knee flexion also begins during this quadrant. Significant GAS recruitment during Quadrants 2, 3, and 4 are also influenced by significant changes in varus/valgus angle between push and pull phases.

A significant interaction effect, cadence by phase, was observed for GAS. EMG area for GAS indicates greater recruitment occurred at 90-rpm than 60-rpm for nearly all phases of a crank cycle. The only portion of a crank cycle in which 90-rpm was not significantly larger than 60-rpm, was at and shortly after ATP. Near ATP and ABP, GAS acts synergistically with ATIB to produce optimal reaction forces and facilitate a smooth transition from one phase of motion to the other.

Ankle Dorsiflexion

Data for ATIB indicated that no significant differences in EMG area were present among pedals. Pedal design did not appear to influence recruitment of this muscle during a crank cycle.

EMG data for ATIB indicated that no significant differences existed between cadences. Cadence did not appear to influence recruitment of this muscle during a crank cycle.

Significant differences in EMG area were observed among phases for ATIB. ATIB was recruited to a significantly greater extent during the push phase than during the pull phase. Peak recruitment occurred during Phase 2. During push phase, ATIB does not produce ankle motion. It acts as an agonist to GAS and provides stabilization to the ankle. ATIB dorsiflexes the ankle during pull phase. ATIB acts synergistically with GAS to optimize reaction forces from the ispilateral limb near ATP and ABP. Near ABP, ATIB stabilizes and dorsiflexes the ankle. Ankle dorsiflexion increases the capacity for knee flexion. ATIB contraction increases tension in GAS, making GAS more effective as a knee flexor.

A second order interaction, pedal by cadence by phase was observed for ATIB. For both cadences, Phase 2 was greater than Phase 1, Phase 1 was greater than Phase 3, and Phase 3 was greater than Phase 4. This pattern was also observed among pedals. For pedals by cadences, clip and flat produced greater EMG areas at 90-rpm than at 60-rpm. Clip was greater than flat at each cadence. Time pedals produced different results. ATIB was recruited to a significantly greater extent at

60-rpm than at 90-rpm. At 90-rpm, clip recruited ATIB to a significantly greater extent than time.

CHAPTER V

SUMMARY, FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The problem of this study was to compare the lower limb kinematics and EMG activity of three bicycle pedal designs. The subjects were male and female students at Western Michigan University. All subjects were volunteers, healthy, and between the ages of 18 and 29, and they stated that they rode a bicycle for recreational or fitness purposes.

The pedals investigated were a flat pedal platform and two different clip-in pedal designs. The platform pedals were lightweight aluminum pedals from Shimano (Shimano American Corporation, Irvine, CA). The clip-in pedals examined were the SP-M747 from Shimano (Shimano American Corporation, Irvine, CA) and the ATAC pedal by time. The SP-M747 pedals provided adjustable cleat tension. This allowed the rider to alter the amount of force necessary to exit the pedal. The pedals were placed at an equal retention setting for all subjects. This model offered 8° of rotational float. The ATAC pedal offered 10° of rotational float. Both clip-in designs allow the cleat to be installed to place the tibia in external rotation, internal rotation, or a neutral position. Subjects were allowed to use their own cycling shoes, but cleats were placed in a neutral position (0° of tibial rotation) at the head of the third metatarsal for all subjects during the clip-in conditions

All subjects performed the trials on the same bike, the pedals were changed between trials. Trials were performed consecutively so that seat height was identical for all trials. Seat height was set to allow 15° of knee flexion at ABP. The ergometer selected for this study was the Fluid+ Trainer by Cycleops, New York. All subjects pedaled against the same load. The ergometer was set to stage three. The bike used was a 21-speed all terrain bike. The bike was placed in gear position eleven. The bike frame was placed in the ergometer such that the axle of the rear wheel was centered in the resistance unit. The front tire rested on the floor. Cadence was monitored by a Pico Club metronome by Sieko (Japan), set at 60 or 90 beats per minute.

The EMG equipment used for this study was a Myosystem 2000, Noraxon, Pheonix , AZ. Peak Motus (Peak Performance Technology, Inc.) was used to synchronize the EMG data with the video data. EMG electrodes used in this study were Medi-Trace Pellet (Graphic Controls Corp., Buffalo, NY) silver-silver chloride disposal.

Video data was captured with two Panasonic cameras (Panasonic Industrial Factory Service Center, Secaucus, NJ): (1) a WV-D5100HS, and (2) a AG-450. These cameras with zoom lenses were genlocked.

A Panasonic model AG 7350 SVHS video recorder attached to a Sony Trinitron 13" diagonal video monitor was used to transfer sections of the tape to be analyzed by the computer. The software used to capture the video images, digitize the motion, smooth the data, and calculate variables was Peak Motus System, Peak Performance Technologies, Inc.

Trials consisted of five complete cycles of motion, beginning and ending at ATP, at two cadences under each of the three pedal conditions.

Findings

The findings for this study were significant at the 0.05 level. The ANOVA calculations were:

1. A significant difference in ankle angle was found among pedals at the 90°, $F(2, 65) = 4.64$, $p < 0.05$. The means for the clip, flat, and time pedals were 116.22°, 115.68°, and 118.45°, respectively. A Tukey HSD test was calculated to determine which of the pairwise comparisons of pedals were significant. The results indicated a significant difference between the flat and time pedal. All other pairwise comparisons were not significant.

2. A significant difference in ankle angle was found between cadences at the ABP position, $F(1, 65) = 9.21$, $p < 0.05$. The mean for the 60-rpm cadence, 128.03°, was smaller than for the 90-rpm cadence, 130.17°.

3. A significant difference in thigh angle was found between cadences at the 270° position, $F(1, 65) = 20.39$, $p < 0.05$. The mean for the 60-rpm cadence, 46.28°, was greater than for the 90-rpm cadence, 44.64°.

4. A significant difference in ankle angle was found between cadences at the 270° position, $F(1, 65) = 7.73$, $p < 0.05$. The mean for the 60-rpm cadence, 119.63°, was smaller than for the 90-rpm cadence, 122.00°.

5. A significant difference in the varus/valgus angle was found among the pedals, $F(2, 143) = 3.28$, $p < .05$. The means for the clip, flat, and time pedals were 34.67°, 32.73°, and 33.69°, respectively. Results of the Tukey HSD multiple comparison test revealed a significant difference between the flat and clip pedals.

6. A significant difference in the varus/valgus angle was found between phases, $F(1, 143) = 62.34$, $p < .05$. The means for the push and pull phases were 31.26° and 36.13°, respectively.

7. A significant difference in the varus/valgus angle was found between cadences, $F(1, 143) = 4.17$, $p < .05$. The means for the 60-rpm and 90-rpm cadences were 34.33° and 33.07°, respectively.

8. A significant difference in EMG area was found among the phases for the rectus femoris muscle, $F(3, 253) = 35.94$, $p < .05$. The means for Phases 1, 2, 3, and 4 were 193.15 μv·s, 111.83 μv·s, 98.60 μv·s, and 153.45 μv·s, respectively. The Tukey HSD multiple comparison test was run to determine significant differences between pairs of phases. Differences existed between: (a) Phase 3 and 4, (b) Phase 1 and 3, (c) Phase 2 and 4, (d) Phase 1 and 2, and (e) Phase 1 and 4.

9. A significant difference in EMG area for the vastus lateralis was found between cadences, $F(1, 253) = 14.17$, $p < .05$. The means for the 60-rpm and 90-rpm cadences were 98.18 μv·s and 87.24 μv·s, respectively.

10. A significant difference in EMG area for the vastus lateralis was found among phases, $\underline{F}(3, 253) = 10.22$, $\underline{p} < .05$. The means for Phase 1, 2, 3, and 4 were 97.23 µv·s, 81.43 µv·s, 89.42 µv·s, and 102.75 µv·s, respectively. The Tukey HSD multiple comparison test indicated significant differences between the following pairs of means: (a) Phase 1 and 2, (b) Phase 2 and 4, and (c) Phase 3 and 4.

11. A significant difference in EMG area for the vastus medialis was found among phases, $\underline{F}(3, 253) = 41.85$, $\underline{p} > .05$. The means for Phase 1, 2, 3, and 4 were 144.16 µv·s, 96.00 µv·s, 92.04 µv·s, and 128.72 µv·s, respectively. The Tukey HSD test for multiple comparisons indicated significant differences between the following pairs: (a) Phase 3 and 4, (b) Phase 1 and 3, (c) Phase 2 and 4, and (d) Phase 1 and 4.

12. A significant difference in EMG area for the medial hamstrings was found between cadences, $\underline{F}(1, 253) = 4.25$, $\underline{p} > .05$. The means for the 60-rpm and 90-rpm cadences were 116.72 µv·s and 102.42 µv·s, respectively.

13. A significant difference in EMG area for the medial hamstrings was found among phases, $\underline{F}(3, 253) = 35.09$, $\underline{p} < .05$. The means for Phases 1, 2, 3, and 4 were 102.37 µv·s, 133.41 µv·s, 100.30 µv·s, and 87.24 µv·s, respectively. The Tukey HSD test indicated significant differences between the following pairs of phases: (a) Phase 1 and 4, (b) Phase 2 and 4, (c) Phase 2 and 3, and (d) Phase 1 and 2.

14. A significant difference in EMG area was found among phases for the biceps femoris, $\underline{F}(3, 253) = 42.76$, $\underline{p} > .05$. The means for Phase 1, 2, 3, and 4 were 126.30 µv·s, 168.43 µv·s, 105.89 µv·s, and 98.86 µv·s, respectively. The Tukey

HSD test indicated significant differences between the following pairs of phases: (a) Phase 1 and 4, (b) Phase 2 and 4, (c) Phase 1 and 3, (d) Phase 2 and 3, and (e) Phase 1 and 2.

15. A significant difference in EMG area was found between cadences for the gastrocnemius, $\underline{F}(1, 253) = 16.99$, $\underline{p} < .05$. The means for the 60-rpm and 90-rpm cadences were 85.87 µv·s and 100.30 µv·s, respectively.

16. A significant difference in EMG area was found among the phases for the gastrocnemius, $\underline{F}(3, 253) = 13.97$, $\underline{p} < .05$. The means for Phases 1, 2, 3, and 4 were 74.63 µv·s, 92.96 µv·s, 101.88 µv·s, and 102.87 µv·s, respectively.

17. A significant first order interaction, cadence by phase was found, $\underline{F}(3, 253) = 3.58$, $\underline{p} < .05$. A graph (see Figure 1) of the means for the phases and the cadences indicated similar responses at Phases 1 and 4. However, at Phases 2 and 3 the gastrocnemius muscle's EMG area was greater for the 90-rpm cadence compared to the 60-rpm cadence.

18. A significant difference in EMG area was found among phases for the anterior tibialis, $\underline{F}(3, 253) = 66.17$, $\underline{p} > .05$. The means for Phases 1, 2, 3, and 4 were 144.55 µv·s, 185.58 µv·s, 121.95 µv·s, and 97.93 µv·s, respectively.

19. The second-order interaction, pedal by cadence by phase, was significant, $\underline{F}(6, 253) = 2.23$, $\underline{p} < .05$. For both cadences, Phase 2 was greater than Phase 1, Phase 1 was greater than Phase 3, and Phase 3 was greater than Phase 4 (Figure 2). This same pattern occurred for pedals and phases (Figure 3). For cadence and pedals (Figure 4), 90-rpm cadence produces a greater EMG area than

the 60-rpm cadence for the clip and flat pedals and the clip pedal had a greater EMG area than the flat pedal for both cadences. However, the patterns produced by the time pedal for both cadences were different from the patterns of the clip and flat pedals. For the time pedal, the 60-rpm cadence had a greater EMG area than the 90-rpm cadence.

Conclusions

The conclusions for this study based on the findings were:

1. Pedal design produced significant differences in lower limb kinematics. Subjects displayed significantly larger ankle angles with time pedals compared to flat pedals during push phase. Clip pedals produced larger varus/valgus angles than flat pedals.

2. Cadence produced a significant effect on lower limb kinematics. An inverse relationship was discovered between ankle angle and thigh and varus/valgus angles. Significantly larger ankle angles were observed at 90-rpm than at 60-rpm. Thigh angle and varus/valgus angle were greater at 60-rpm than 90-rpm.

3. Subjects displayed a varus angle throughout the entire crank cycle. The greatest varus angle was observed during pull phase, and subjects tended to move closer to a neutral position (0° of varus/valgus) during the push phase.

4. Pedal design did not produce any significant differences for any muscle.

5. Cadence did produce significant differences in EMG area. An inverse relationship between EMG area and cadence was observed for VL and MH, EMG area increased as cadence decreased. EMG area for GAS increased with cadence.

6. Significant differences in EMG area were found between phases for all muscles. Knee extensors produced greater EMG areas during the top portion of the crank cycle, Phase 1 and Phase 4. Knee flexors and ATIB produced larger EMG areas during the push phase of the crank cycle, Phase 1 and Phase 2. GAS and ATIB produced larger EMG areas during the pull phase of the crank cycle.

7. The interaction cadence by phase produced larger GAS EMG areas during the lower half of the crank cycle as cadence increased. GAS plays key roles in initiating knee flexion and facilitating smooth pedal movement through ABP. EMG activity could be expected to increase due to increased torque to maintain the higher cadence.

8. Cadence, pedal design, and phase interact to influence the behavior of GAS and ATIB. ATIB activity was different among pedals at each cadence. Clip and flat pedals produced larger EMG areas at 90-rpm, while time pedals produced larger EMG area at 60-rpm.

Recommendations

The recommendations for further study include:

1. Study other pedal designs on the market. Compare effectiveness of other designs to the results of this study.

2. Recruit a larger and more diverse pool of subjects. Assign subjects to groups, competitive and recreational, based on cycling experience.

3. Collect data on joint loads and torques. These data explain joint movement and muscle activity, not how the forces produced from muscle activity affect joint movement and force transmission.

4. Subjects should pedal against different resistance loads. Ideally, subjects could perform trials over variable terrain or with a variable resistance protocol.

Appendix A

Human Subjects Institutional Review Board
Letter of Approval

Human Subjects Institutional Review Board

Kalamazoo, Michigan 49008-3899

WESTERN MICHIGAN UNIVERSITY

Date: 5 November 1998

To: Mary Dawson, Principal Investigator
Dave Lacy, Student Investigator for thesis

From: Sylvia Culp, Chair *Sylvia Culp*

Re: HSIRB Project Number 98-10-09

This letter will serve as confirmation that your research project entitled "A Biomechanical Analysis of Three All-Terrain Bicycle Pedals" has been approved under the expedited category of review by the Human Subjects Institutional Review Board. The conditions and duration of this approval are specified in the Policies of Western Michigan University. You may now begin to implement the research as described in the application.

Please note that you may only conduct this research exactly in the form it was approved. You must seek specific board approval for any changes in this project. You must also seek reapproval if the project extends beyond the termination date noted below. In addition if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: 5 November 1999

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