Towards the Prevention of Handlebar Palsy: The Contribution of Handlebar Shape and Road Grade on Localized Hand Pressures

THESIS

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By

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Abstract

A neuropathy known as handlebar palsy develops when a lesion of the ulnar and/or median nerves takes place due to cyclists bearing their upper body weight on the handlebars of a bicycle (Capitani 2002). This study identified the magnitude and locations of the highest median pressures on the palms of the hands of fourteen road and mountain cyclists. Wrist posture, i.e. ulnar/radial deviation and flexion/extension, was also quantified. Participants were instrumented with a portable data acquisition system with force sensing gloves. Two electrogoniometers were used to capture wrist posture data. The study investigated four road bike grip positions, two mountain bike grip positions, and three road grades (flat ground, uphill, and downhill). It was found that grip position had a significant effect on the highest median pressure values and the location of these pressure values across participants and road grades. It was also found that grip position had a significant effect on ulnar/radial deviation and flexion/extension. These data were used to explore alternative designs and design characteristics that more evenly distribute the pressure on the palm of the hand and place the wrist in a more neutral posture.
Dedication

This is dedicated to my loving family and Randy Patton for getting me on a bike.
Acknowledgments

I would like to thank my entire committee for the hard work and time that they put into my thesis study. I would like to thank Joe West for helping me construct the test equipment. I’d like to thank Leo Rusli for helping me calibrate the force sensors using Dr. Luscher’s Instron Machine. I would also like to thank The Ohio State University for providing me with the resources needed to complete my master’s education.
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Chapter 1: Introduction

Handlebar palsy, also known as "cyclist palsy," is a condition caused by the compression of the ulnar nerve against the handlebar while riding a bicycle. It is associated with road cycling as well as mountain biking. The condition develops from riders bearing weight on their hands while keeping their wrists in extension for an extended period of time (Patterson 2003). This places excessive pressure on the palm of the hand, thus compressing the ulnar and median nerves. An incidence study performed by Patterson (2003) stated that handlebar palsy affects up to 70% of competitive cyclists, both road and mountain. Capitani and Beer (2002) concluded that riders are usually unaware of the compression of the ulnar nerve until a significant lesion develops because sensory disturbances are not always present.

Handlebar palsy is a condition that has become a research focus in recent years. Symptoms have been documented for a number of years (Eckman 1975), and the research performed to date on handlebar palsy has confirmed that it is a serious condition that exists for many cyclists (Patterson 2004; Akuthota 2005). Prior research includes measuring motor and sensory disturbances in the hand and wrist (Patterson 2004; Akuthota 2005). Although the documentation exists that handlebar palsy is indeed a
severe injury, there has been little to no research performed on the methods of injury prevention. A review of the literature reveals that many journal articles mention prevention strategies for handlebar palsy such as having a properly fit bicycle, wearing properly padded gloves, and having properly padded handlebars. They also give no indication of padding type or material, and its effectiveness. However, these articles do not identify how bicycle fit affects pressure on the palm. In addition, padding is a passive or “Band-Aid” solution that does not work for many cyclists. In Patterson’s incidence study, twenty-three of the twenty-five subjects reported wearing padded gloves and two subjects did not indicate whether they did or did not.

The objectives of the current study were:

1. To quantify the forces on the palm of the hand and measure wrist posture in four grip positions on a road bike and two grip positions on a mountain bike.

2. To use test data to guide the design of new handlebars that would reduce exposure to risk factors for handlebar palsy.
Chapter 2: Literature Review

A review of the literature on distal upper extremity ulnar neuropathies due to cycling revealed that handlebar palsy is a prevalent, non-traumatic injury in bicycling. The literature review was performed using Google Scholar, Web of Knowledge, and Web of Science. Various forms of the following keywords were used in the literature search: Guyon’s Canal, Ulnar neuropathies, handlebar palsy, cyclist palsy, nerve entrapment, and bicycling.

The review of the literature revealed case studies dating back to the 1970s as well as electrodiagnostic studies performed within the last decade. In conjunction with the case studies and electrodiagnostic studies, several other articles were included that pertain to handlebar palsy. For example, Silberman (2005) documented the relation between bike fit and the resulting pressure on the palm of a cyclist’s hands. Cobb (1994) showed how the pressure within the carpal tunnel is affected by externally applied loads on specific locations of the palm. Lastly, a review article by Dettori (2006) was provided that summarizes non-traumatic bicycling injuries.
Case Studies

Eckman (1975) performed a case study of a 22-year-old man who had ridden 3,000 miles across the U.S. in 30 days. The man reported weakness of both hands with no sensory disturbances. The man’s symptoms were limited to his hands, with weakness of the dorsal interossei muscles, the abductor digiti minimi, and the adductor pollicis muscles. Eckman concluded that the lesion of the ulnar nerve was of the deep, motor branch. The man was advised to refrain from cycling for several months and significant improvement of strength and muscle function was shown in follow-up visits.

February 1975, the same month that Eckman’s report was published in the Archives of Neurology, a letter to the editor by Smail, M.D., was published in The New England Journal of Medicine entitled, “Handlebar Palsy.” In the letter, Smail reported weakness of the ulnar intrinsic muscles of his own hands after a 2900 km ride in which he rode for ten hours per day. He reported no median nerve paresthesia, and had complete recovery of muscle function after two months without cycling. Smail referred to his symptoms as “handlebar palsy,” and stated that his symptoms had never been reported in the medical literature. This led Smail to pose the question, “Have I received an injury to which no one else is susceptible?”

In March, 1975, Finelli responded to Smail’s letter to the editor of The New England Journal of Medicine. Finelli reported that the neuropathy Smail described had been previously described in the literature by Wolff (1948) with regard to motorcyclists. The
editor of the journal also left a note under Finelli’s letter stating, “Thirteen letters have arrived indicating that ‘handlebar palsy’ is a well-known and well described entity.” The note also referenced Eckman’s article from February, 1975, in the *Archives of Neurology*.

The letters written by Smail and Finelli, as well as the article written by Eckman, show that symptoms of handlebar palsy have been documented for several decades. This shows that bicycle technology over the years has been driven by performance rather than well-being of the cyclist. Although bicycles become more advanced each year, cyclists are still developing the same symptoms that they were nearly forty years ago with regard to ulnar and median entrapment neuropathies. The continued discovery of cyclists suffering from handlebar palsy may also be due to the fact that it’s difficult to diagnose and that many cases go undocumented.

Capitani and Beer (2002) wrote three case studies on patients who developed symptoms of handlebar palsy from cycling. From the case studies as well as a prior review of the literature, Capitani and Beer concluded that “chronic repeated trauma (especially due to stereotyped professional activities) and chronic pressure together with vibration exerted over months or years are well known extrinsic causes of an ulnar neuropathy at the wrist or hand.” In regards to road cycling, the symptoms are caused by “high frequency, repetitive compression,” and the amount of time spent cycling is a critical factor in the onset of the symptoms. However, with regard to mountain bikes, Capitani and Beer concluded that the onset of handlebar palsy is possible after “a single, short exposition.”
They presumed that this is due to changes in handlebar geometry that result in hyperextension of the wrist with “repeated blows on Guyon’s Canal.”

Capitani and Beer (2002) described four types of handlebar palsy. The four types are described in Table 1.

Table 1: Four Types of Handlebar Palsy

<table>
<thead>
<tr>
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<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Type 4</th>
</tr>
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<tbody>
<tr>
<td>Location of Lesion</td>
<td>Lesion proximal to Guyon’s Canal, before it splits into the superficial and profundus branches (see Figure 1).</td>
<td>Lesion of the deep motor branch of the ulnar nerve within Guyon’s Canal</td>
<td>Lesion of motor branch distal to Guyon’s Canal</td>
<td>Lesion of the sensory branch of the ulnar nerve</td>
</tr>
<tr>
<td>Motor/Sensory Function</td>
<td>Loss of sensory function and weakness of all ulnar intrinsic hand muscles</td>
<td>No sensory losses and weakness of all ulnar intrinsic hand muscles</td>
<td>Weakness of the dorsal interossei muscles, leaving the hypothenar muscles functional</td>
<td>Complete sensory loss and complete functionality of the ulnar intrinsic hand muscles</td>
</tr>
</tbody>
</table>
Capitani and Beer (2002) concluded that the most common lesions of the ulnar nerve from cycling are usually of the deep motor branch, types two and three. They provided the reasoning that, “the outlet of Guyon’s Canal is particularly narrow predisposing for isolated mechanical lesions of the deep motor branch at this site.”

The first subject of the Capitani and Beer (2002) case reports developed handlebar palsy after a 5000 km, 9 day ride on a road bike. He developed a lesion of the deep motor branch of the ulnar nerve, with weakness of the all ulnar intrinsic muscles (Type II). He recovered almost entirely after three months of avoiding “sports in which the hand is
underlying any pressure at the wrist.” The second subject developed symptoms of handlebar palsy after about two days of mountain biking. This subject also had a lesion of the deep motor branch, losing motor function of the dorsal interossei muscles, but not the hypothenar muscles (Type III). The subject gradually regained strength in the hand over the “next months” while avoiding cycling. Lastly, the third subject was an inexperienced mountain biker who developed the symptoms after “a single downhill mountain bike trip.” The subject recovered completely after three months of no cycling, but did not take up cycling again for a full year. All three cases show that while handlebar palsy is not a permanent condition, it is serious enough to warrant restriction from any form of compression of the palm with the wrist in extension for extended periods of time.

The report by Capitani and Beer concluded with the statement, “The growing popularity of mountain biking may increase the number of people with handlebar palsies: clinicians must be aware of this particular problem advising people on precautionary measures before starting and during intensive biking training.” This is very similar to the concluding remarks by Eckman, nearly thirty years earlier, “With the present increase in the use of bicycles for transportation and recreation, we anticipate that this compression neuropathy will be seen more frequently.” It is interesting to note that although the symptoms have been documented for a number of years, little work has been found to directly address the causes of handlebar palsy. Recommendations for prevention by Capitani and Beer (2002) included adjusting the seat height and wearing padded gloves.
Reddy (2004) wrote a case report about handlebar palsy and a brief literature review. The subject of the case report was a 47-year-old woman who showed clawing and decreased sensation of the fourth and fifth digits along with decreased strength. Electromyography and nerve conduction studies revealed that the lesion of the ulnar nerve was of the deep motor branch, “just distal to the origin of the digital sensory nerves.” An MRI revealed that the subject had no abnormalities within Guyon’s Canal. The subject recovered completely from motor and sensory dysfunction after four months without cycling. Consistent with Capitani and Beer (2002), Reddy concluded that “horn” handlebars and rider posture were the factors responsible for causing this condition.

Smith (2008) sought to find the incidence of the double crush syndrome in cyclists that have been diagnosed with a distal ulnar nerve neuropathy, known as cyclist’s palsy. The double crush syndrome refers to the predisposition of a second nerve injury when an individual already suffers from an injury to the same nerve. In this study, Smith performed clinical tests suggestive of thoracic outlet syndrome (TOS) in the upper limbs of cyclists with a clinical diagnosis of cyclist’s palsy. The same tests were performed on the upper limbs of cyclists who did not show any signs of cyclist’s palsy. In this study, thoracic outlet syndrome referred to pain in the arm, neck, and shoulder. There were 70 cyclists between the ages of 18 and 65 years in the study who rode their bicycles for a minimum of 45 minutes three times per week. The subjects filled out a questionnaire prior to testing to obtain the amount and type of cycling performed by the subject, the
medical history of the subject, and personal demographics of the subject. Subjects were excluded if they rode recumbent bicycles, were pregnant, had surgeries related to TOS, or had surgeries related to distal upper limb syndromes.

The upper limbs of the cyclists in the study were classified as either positive for an ulnar nerve neuropathy [ULNN (+)] or showing no signs of an ulnar nerve neuropathy [ULNN(-)]. The ULNN(+) subjects reported subjective sensory or motor disturbances of the hand and wrist in the six months prior to the study. The upper limbs also had to test positive for one of the three examinations:

“(1) diminished sensation in the ulnar nerve territory using the Semmes-Weinstein monofilaments on the 5th digit, with values greater or equal to 3.61 mg/force; (2) diminished strength of the intrinsic muscles of the abductor digiti minimi measured as being more than 2 standard deviations (SD) below normative data of subjects hand dominance and gender matched, as measured using the Rotterdam Intrinsic Hand Myometer; and (3) symptom reproduction in the ulnar nerve distribution using the elbow flexion pressure provocation test at 60 seconds.”

The ULNN(-) subjects reported no subjective complaints of an ulnar nerve neuropathy. Seventy-two of the 140 upper limbs were excluded because the subjects complained of symptoms but did not test positive for one of the three physical examinations.
The physical examinations performed on the subjects for signs of TOS included: an elevated arm stress test, a modified cyriax release test, and an elevated first rib test. Images of the three examinations can be seen in the Appendix section of this thesis.

Smith found that 32% of ULNN(+) subjects tested positive for the elevated arm stress test, whereas only 4% of ULNN(-) tested positive for the same test. For the cyriax release test, 43% of ULNN(+) subjects tested positive whereas only 7% of ULNN(-) subjects tested positive. Smith also found that ULNN(+) subjects were 13 times more likely to have an elevated first rib than ULNN(-) subjects. Neck pain was three times more prevalent in ULNN(+) subjects and shoulder pain was five times more likely in ULNN(+) subjects.

Smith’s study revealed a high rate of symptoms of thoracic outlet syndrome for ULNN(+) subjects. This suggested a strong correlation between cyclist’s palsy and the double crush syndrome, and therefore a high prevalence of the double crush syndrome in cyclists with an ulnar nerve neuropathy. This is a critical study because it reveals that a large percentage of cyclists with handlebar palsy are susceptible to developing pain in other parts of the body, namely the arm, shoulder, and neck. Smith concluded that the study could be used to inform cyclists that frequent changes in position of the neck, shoulder girdle, and hands may be critical in lowering the prevalence of ulnar nerve neuropathies in cyclists, and therefore the double crush syndrome.
Prospective Incidence Studies

Patterson (2003) sought to determine the incidence of “distal ulnar nerve compression” in cyclists. The study examined nine mountain cyclists and sixteen road cyclists who were chosen at random among 1800 cyclists competing in a 4-day, 600-km ride. The subjects completed a questionnaire before the ride to obtain rider experience and medical history. Baseline measurements were also taken before the ride of motor and sensory function of the ulnar and median nerves. After the fourth day of the ride, the 25 subjects were again tested for motor and sensory function. Motor function was tested by grip and pinch meters, and symptoms of Froment’s sign were documented. A positive indication of Froment’s sign refers to the inability to grip a piece of paper between the thumb and flat palm as the paper is pulled away. Sensory function was examined by performing Phalen’s maneuver and documenting the existence of Tinel’s sign. Phalen’s maneuver is a test for carpal tunnel syndrome in which the subject is asked to hold their wrist in extension for thirty to sixty seconds. If numbness and tingling are felt in the thumb, index, middle finger, and ring finger, the subject shows positive signs of carpal tunnel syndrome. Tinel’s sign refers to the method of lightly tapping a nerve to incite tingling throughout the nerve. The subject tests positive for Tinel’s sign if a tingling sensation is felt. Subjects were also asked to report sensory disturbances in the portions of the hand innervated by the ulnar and median nerves. All tests were performed between four and six hours after the completion of the ride in order to eliminate fatigue as a potential cause of motor disturbances.
Patterson (2003) found that 70% of the subjects experienced motor disturbances, sensory disturbances, or both. Motor disturbances were found in 36% of the hands tested, sensory disturbances were found in 10% of the hands tested, and both motor and sensory disturbances were found in 24% of the hands tested. Mountain cyclists were found to have a greater incidence of sensory disturbances than road cyclists, 44% (4/9 cyclists) as compared to 12.5% (2/16 cyclists). Patterson concluded that this is most likely the result of having fewer options for hand positions on mountain bike handlebars. However, it is also likely that the “knobby” tires of a mountain bike are more likely to induce vibrations in the handlebars. There was no statistically significant correlation between rider experience and incidence of motor or sensory symptoms. This is an important conclusion, because it implies that riders of any experience level can develop the symptoms just as easily as experienced, competitive cyclists. Patterson classified rider experience by the number of kilometers ridden by the subject per week in the two months leading up to the event. The subjects were also asked to subjectively input their experience level as beginner, intermediate, and advanced. Patterson also concluded that sensory deficits were more prevalent in the ulnar nerve than median nerve, which was most likely due to “localized pressure over and distal to Guyon’s Canal.” Patterson (2002) concluded by suggesting the following prevention strategies: wearing properly padded gloves, changing hand positions frequently, and having the bike properly fitted.

Patterson (2002) performed a prospective study on handlebar palsy as opposed to the previous authors who had only written case studies. However, there were still several
limitations of this study. The sample size of subjects was small, 25 riders (16 road bikes; 9 mountain bikes; 23 subjects wearing gloves), and he did not follow up on the subjects to evaluate their symptoms for extended periods of time after the race. This left no indication of the length of time that the subjects experienced the symptoms. Patterson, understanding the limitations of his test, mentions that an electrodiagnostic study on a larger sample size would be a better determinant of the incidence of handlebar palsy. Final recommendations from the study include wearing padded gloves, adjusting the seat height (higher or lower not indicated), and changing hand position frequently.

**Electrodiagnostic Studies**

Akuthota (2005) hypothesized that electrophysiologic changes would be present in the ulnar and median nerves after a long-distance multi-day cycling event. He examined fourteen subjects that completed a 6-day, 420-mile bike tour. None of the subjects reported symptoms of handlebar palsy before the ride, but three subjects showed signs of carpal tunnel syndrome when baseline measurements of the ulnar and median nerves were taken. All three of these subjects showed worsening of the median motor latency times after the ride, thus worsening their symptoms of carpal tunnel syndrome. For the ulnar nerve, Akuthota found that, “onset motor latencies were significantly prolonged for the deep branch of the ulnar nerve to the FDI (first dorsal interosseus).” This suggests that the lesion of the ulnar nerve develops “in the palm, distal to the motor branch to the ADM (abductor digiti minimi).” This conclusion is consistent with Capitani and Beer’s (2002) findings.
Akuthota measured motor and sensory latency times within three hours of the completion of the 6-day ride. This contrasts with Patterson’s approach to test the subjects between four and six hours after the ride to eliminate muscle fatigue as a contribution to motor disturbances. The fact that Akuthota’s subjects were tested shortly after the ride may have contributed to the motor latency times. Akuthota also did not follow up with the subjects to see how long their symptoms persisted.

**Cadaver Studies**

Cobb (1995) used five cadaveric upper limbs in a study to determine how pressure applied to the palm of the hand affects the pressure in the carpal tunnel. A one kilogram force was applied to sixteen different locations on the palms of the five cadaver hands, as seen in Figure 2 below. Pressures were measured using a MIKRO-TIP transducer system at the hook of the hamate bone. Figure 2 below shows the sixteen locations of the palm with the corresponding average carpal tunnel pressures in millimeters of mercury.
Cobb found that pressures applied to the distal region of the palm, positions 1, 4, 7, and 10, had little effect on carpal tunnel pressure. Similar results were found for the next proximal row, positions 2, 5, 8, and 11. Significant pressures were measured at locations 9, 6, 13, 14, and 15, where positions 13, 14, and 15 were directly over the transverse carpal ligament. Cobb concluded that significant pressures at locations 9 and 6 were due to three possible reasons. The first possible reason is that the pressure on the thenar and hypothenar muscles at these locations causes the transverse carpal ligament to stretch, thus increasing the pressure within the canal. The second possible reason is that the forces applied at locations 9 and 6 distribute the pressure to the flexor tendon sheaths through “compartmental anatomy.” The third possible reason for the increase in pressure is that the compression of the soft tissue distributes the pressure to adjacent tissues.
There have been no studies found relating pressures on the palm to ulnar nerve compression. Due to this, it is important to consider the results of locations 9 and 6. These results show that areas of the palm that are not directly over the ulnar nerve may contribute significantly to the compression of the ulnar nerve. Some of the pressures measured in Cobb’s study were above the threshold where pressure has been shown to affect nerve function, that is, above 30 mmHG (Rydevik et al. 1981). However, Cobb noted that the pressures would have to be applied over a substantial duration to have an effect. This becomes extremely critical in long distance cycling because the pressures are applied over extended periods of time.

Bicycle Fit Study

Silberman (2005) addressed handlebar palsy in relation to bike fit. Silberman states, “Contributing factors may be bars positioned too low or a saddle too far forward or tilted downward. Hand symptoms may be rectified by increasing handlebar padding (gel or foam not indicated), changing hand position frequently, adjusting handlebar tilt and/or height, and rechecking the saddle height.” The suggestions provided by Silberman (2005) are mentioned throughout the literature, however Silberman (2005) made more specific claims with regard to the contributing factors. For instance, Silberman (2005) notes that a contributing factor may be handlebars positioned too low, rather than stating “improper handlebar height.”
Silberman (2005) assessed the proper fit of a road bicycle in relation to comfort, safety, injury, and performance. Silberman enforced the fact that the proper fit of a bicycle is a balance between all of these factors and it is specific to each cyclist. He stated that the fit of the bicycle is dependent on both static and dynamic measurements. The static measurements include the shoe-pedal interface, saddle (seat) height, saddle fore-aft position, saddle tilt, stem height, handlebar height, and stem length. The dynamic fit measurements include pedal torque and spin analysis.

The following summarizes some general guidelines for the static measurements on a road bicycle, as provided by Silberman. The rules provided are not the only methods addressed by Silberman for obtaining the proper fit of a road bicycle. One method of obtaining the proper position of the shoe on the pedal is to have the first metatarsal head lying directly over the pedal axle, as seen in Figure 3.

Figure 3: Shoe Position (Silberman 2003)
The saddle height should be adjusted such that the leg is nearly fully extended, i.e. 25° to 30° flexion of the knee, at the bottom of the pedal stroke, as seen in Figure 4.

Figure 4: Angle of Knee (Silberman 2003)

The fore-aft position of the saddle should be adjusted such that the inferior pole of the patella lies directly over the pedal axle, as seen in Figure 5, to achieve optimum transfer of power to the crank from the muscles of the legs.
The saddle tilt should be adjusted such that it is close to level or parallel to the ground. Stem and handlebar height are subjective but a recommended measurement is a 5-8 cm vertical distance between the top of the saddle and the top of the handlebars, as Figure 6 shows.
The angle of the cyclist’s back should also be approximately 45° with respect to the ground, as seen in Figure 5, for proper alignment of the torso. The stem length should be adjusted such that is neither bunched up nor stretched out, and this is generally achieved with a stem length of 10-12 cm with a properly sized bike frame.

**Review Articles**

Dettori (2006) wrote a review of the literature entitled *Non-Traumatic Bicycle Injuries*. In the review, Dettori stated, “Two categories of injuries that may have the greatest impact on disability include ulnar and median nerve palsy, and erectile dysfunction.” Dettori stated that handlebar palsy is a “compression syndrome” and that the location of compression is usually of the deep motor branch of the ulnar nerve. He stated that compression of the motor and sensory branches of the ulnar nerve may occur, however. Dettori mentioned that compression of the median nerve is also possible, but less common. He concluded that this is most likely a result of riding on “the hoods (where the brake lever attaches to the handlebars [of a road bicycle]).” Dettori concluded the review of hand and wrist injuries by stating that prevention strategies, such as wearing properly padded gloves and frequently changing hand positions on the handlebars, have never been tested for their effectiveness in preventing symptoms of handlebar palsy.

**Summary**

A review of the literature reveals that handlebar palsy is a serious injury that affects up to 92% of cyclists (Patterson 2003: 23 of 25 subjects), and may prevent affected cyclists from riding and performing daily activities such as writing and typing for several months.
(Capitani and Beer 2002). Much of the literature proposes prevention strategies, but the effectiveness of these strategies has not yet been investigated in academia. The common prevention strategies include having a bike properly fit, changing hand positions frequently, wearing padded gloves, and having padded handlebars. However, as Patterson (2003) found, the incidence of handlebar palsy is still very high even with cyclists who wear gloves (23 of 25 subjects wore padded gloves).

When looking at methods to prevent handlebar palsy, there are several avenues for improvement. As mentioned, many authors recommend padded gloves and padded handlebars. In general, proper protective equipment such as padding is usually a last line of defense. In addition, padding itself has very different properties if it’s made of foam or gel. Beyond padding, a second method of preventing handlebar palsy that is suggested by many authors is having the bike properly fitted. However, bike fit is largely determined to optimize efficiency, and no matter how the bike fits, cyclists will always have to support their upper bodies with their hands on the handlebars. This being said, the design of the handlebar has not been investigated for its effectiveness at placing the wrist in a neutral posture and distributing forces throughout the palm of the hand. Therefore, the objectives of the current study were:

1. To quantify the forces on the palm of the hand for three levels of road grade, in four grip positions on a road bike and two grip positions on a mountain bike.

2. To quantify the posture of the wrist, namely flexion/extension and ulnar/radial deviation as a function of grip position and road grade
3. To use test data to guide the design of new handlebars that further prevent handlebar palsy.

This study is exploratory, as the pressure distribution on the palm of the hand for varying grip positions and road grades has not yet been published within academia. Given the objectives, the associated hypotheses were:

1. Grip position will have a significant effect on the pressure distribution on the palm of the hand, as well as the posture of the wrist for road and mountain bike handlebars.

2. Road grade will have a significant effect on the pressure distribution on the palm of the hand, as well as the posture of the wrist.
The test equipment used in this study was designed explicitly for the study. The equipment included twelve flexible piezo-electric force sensors to measure the forces on the palm of the hand, two electrogoniometers to measure flexion/extension and ulnar/radial deviation of the wrist, and an accelerometer to distinguish between the different portions of the trials. The devices were powered by a Toshiba Satellite Laptop (2.13 GHz i3 Intel Pentium Processor with 4 GB Memory); a LabJack U3-HV data acquisition system was used to connect and read-in all of the devices. The system was configured using DAQFactory Express free-ware software. The system was designed to be entirely portable, fitting in a backpack, to allow for testing under the most realistic riding conditions. The system was also designed with user-centered design principles to ensure that the subjects were comfortable at all times. For instance, plugs were soldered into every wired connection of the system, ensuring that the subject could be fully instrumented without wearing the backpack, and therefore holding the weight of the laptop and DAQ on their back.
The following figures show a top-level view of the actual test equipment, and the associated circuit diagrams. The devices are then dissected in the succeeding sections of this chapter.

Figure 7: Test Equipment showing DAQ (in gray circuit box, left), force gloves with associated drive circuits (in iPod arm bands), electrogoniometers, and accelerometer (black circuit box)
The force sensors used for the study were Tekscan® Flexible Piezo-Resistive FlexiForce Sensors. The sensors chosen were rated to 100lb$_f$ per sensor (Tekscan® model A201). The sensors contained a 0.375” diameter sensing area, and were adhered to Φ0.5”, 0.0625” thick aluminum disks using Sunshine® toupee tape. The aluminum disks were adhered to plastic buttons (0.0625” thick) that were arranged in a three by four grid on thin, synthetic-leather palms of Mechanix® Original Gloves, size large. Six sensors were mounted on each palm, as seen in Figure 9 below, in offset locations. Assuming symmetry of the hands on the handlebars of the bicycle, the twelve sensor grid was
created between the two hands. The buttons were sewn-on in all twelve locations of both palms, providing a consistent feel between both hands when riding the bicycle.

Figure 9: Pressure Sensing Gloves (left); Sensor Positions on the Left Hand when the Data from the Two Gloves are Combined (right)

Each of the flexible sensors had its own drive circuit. The drive circuits were soldered to a 417-hole, multi-purpose PC board from RadioShack®. The boards were housed in iPod arm bands for protection, as seen in Figure 10 and the arm bands were strapped to the subjects’ forearms. Due to the fact that these armbands are intended for upper-arm use, electrical tape was often wrapped around the band to provide a more snug fit when testing.
The drive circuit for one of the sensors can be seen in Figure 11. A hard-wired low-pass filter with a 100μF capacitor and 180Ω resistor ($f_c = 8.8$Hz) was used to smooth out some of the higher frequency noise from the surroundings, such as the laptop computer. The FlexiForce sensors were supplied with a -5V, as per the instruction manual. The -5V was provided by Dimension Engineering Negatron® DC-DC converter, which can be seen in Figure 15.
Electrogoniometers

There were two electrogoniometers used for this study, one measuring flexion/extension and the other measuring ulnar/radial deviation, which have been used in previous published research by Marras and Schoenmarklin (1993). Each electrogoniometer consisted of a potentiometer, about which two thin aluminum tabs pivoted. As the angle of the potentiometer changed, a needle swept over a resistor within the potentiometer, thus changing the resistance and therefore the output voltage. The electrogoniometers were instrumented on the subject for static tests, within the lab. This decision was based
on the hypothesis that wrist posture is relatively static when riding in a specific grip position without applying the brakes, and independent of a 5% grade hill.

As seen in Figure 12, an electrogoniometer was placed on the dorsal side of the palm in order to measure ulnar/radial deviation.

![Electrogoniometer Measuring Ulnar (bottom) / Radial (top) Deviation](image source: badmintoncentral.com)

Figure 12: Electrogoniometer Measuring Ulnar (bottom) / Radial (top) Deviation (right image source: badmintoncentral.com)

The electrogoniometer was placed at the pivot point of the wrist, above the inferior radioulnar joint. The thin aluminum tabs were aligned such that there was 180° between tabs when the wrist was in a neutral posture. However, the “zero-deviation” point was found by having the subject rest in a neutral posture after the electrogoniometers were adhered, and taking a measurement. For setup, the subject sat at the edge of a table, with the forearm resting on the table and parallel to the table’s edge.
The second electrogoniometer was placed on the ulnar side of the wrist, as seen in Figure 13.

Figure 13: Electrogoniometer Measuring Flexion (bottom) / Extension (top) of the wrist (right image source: badmintoncentral.com)

The electrogoniometer was placed at the pivot point of the flexion/extension motion of the wrist. The thin aluminum tabs were aligned such that they were 180° with respect to each other with the wrist in a neutral posture, and a “zero-deviation” measurement was made. As seen in the diagram, neutral posture does not imply that the entire palm makes contact with the table surface. The aluminum tabs were adhered to the subjects using 3M foam medical tape.

The circuit diagram shows the connections of the electrogoniometers. These devices provided a voltage output and required a voltage source, 5V for this application, and the ground in order to operate. The circuit diagram can be seen in Figure 14.
The two goniometer signals were multiplexed for this test setup. This is because the LabJack U3HV could only handle 16 inputs, and there were originally 18 signals, as discussed below. The multiplexer circuit is shown in Figure 15.
The multiplexer circuit was set to sample at 100Hz within the DAQ software, with a switching frequency of 10Hz using a NE555P timer chip with a 56kΩ resistor. Also pictured in the above diagram are the two devices that were not used in final testing. The two devices were an SCA61T-FA1H1G inclinometer and an EE-SY310 proximity sensor. The inclinometer was placed on the bike and was initially to be used to measure the grade of the hill, and provide the position of the cyclist at all times. This device was not used in final testing because of the intense vibration on the bicycle, the large
instantaneous deviations in the grade due to an imperfect surface, and the relatively low angle of the hill (5% grade = 2.5\(^\circ\)).

The proximity sensor, working as a digital on/off switch, was initially to be used to identify when the subject was applying the brakes. It was to be mounted on the brake handle such that as the lever was squeezed, a reflective surface mounted on the handle would no longer reflect the optical signal back to the sensor. This sensor was not used in final testing because it was unreliable, and the controlled braking locations within the test course were sufficient to isolate braking from non-braking periods in the data streams.

The proximity sensor and the inclinometer were also multiplexed signals, as seen in Figure 15. As mentioned earlier, the DAQ could only handle 16 inputs, and 18 were required initially (12 force sensors, two goniometers, inclinometer, proximity sensors, and two outputs of a two-axis accelerometer).

**Accelerometer**

A Dimension Engineering DE-ACCM 5g buffered two-axis accelerometer was mounted on the bicycle. The accelerometer was housed in a small project box, and mounted to the top tube of the bicycle using a hose clamp. A thin layer of pipe insulation was used to protect the paint on the bike frame. The accelerometer was a two-axis device, and it was mounted on the bicycle such that it could measure forward accelerations/ decelerations as well as vibrations. However, the forward accelerations/ decelerations were too heavily influenced by the vibrations on the bicycle. Therefore, the accelerometer was used
simply to distinguish the different portions of the trials in post-processing. The subjects were asked to come to complete stops and put one foot on the ground between the different portions of the trials. This was to ensure that the accelerometer stabilized, and natural breaks in the data could be discerned. The circuit diagram in Figure 16 shows that the accelerometer simply needed a 5V supply and ground to operate.

![Circuit Diagram for DE-ACCM Accelerometer](image)

**Figure 16: Circuit Diagram for DE-ACCM Accelerometer**

Future testing might utilize an accelerometer by damping out vibrations and applying a low pass filter in post-processing.

**DAQFactory Express**

The software used for data collection was a freeware package called DAQFactory Express. This software was configured for the recording of sixteen inputs in real time.
from the LabJack U3-HV. This software is designed to operate specifically with the LabJack. Please refer to http://www.azeotech.com/dl/usersguide.pdf for the full user manual for DAQFactory Express. Within the software, the sixteen channels were configured for the inputs, as seen in the right-hand side of Figure 17.

![Figure 17: DAQFactory Express Software](image)

Within the channel configuration menu, the sample rate of the force sensors was set to 10 Hz and the sample rate of the other devices was set to 100 Hz. The logging option within the program was used to save the data that was recorded in real-time. Lastly, two blank “PAGES” are provided within the software in order to display the data that’s recorded in real-time. On these pages, sixteen 2-D plots were configured to display each of the inputs.
Chapter 4: Localized Hand Pressures when Riding a Road Bike: The Effects of Grip Position and Road Grade

Abstract

A neuropathy known as handlebar palsy develops when a lesion of the ulnar nerve takes place due to cyclists concentrating the weight of their upper body on their hands while their hands grasp the handlebars of a bicycle (Akuthota 2005, Patterson 2003). The objective of this study was to identify the magnitudes and locations of the forces on the palms of the hands of 14 road cyclists, while also measuring wrist posture. While riding, participants wore force sensing gloves that were connected to a portable data acquisition system. The study investigated four road bike grip positions and three road grades. Grip position significantly affected the total force on the hand, the force distribution across the hand, and the posture of the wrist, independently of road grade. These data can be used to guide the design of handlebars that would more evenly distribute the pressure on the palm of the hand.

Introduction

Handlebar palsy, also known as "cyclist palsy", is a nerve condition caused by the compression of the ulnar nerve in the palm of the hand while riding a bicycle (Akuthota 2005). It develops from riders bearing their upper body weight on their palms while
gripping the handlebar, and it is associated with road cycling, as well as mountain biking (Capitani 2002, Patterson 2003). Handlebar Palsy affects both competitive and recreational cyclists, and the symptoms are dependent on the location and severity of the nerve lesion (Akuthota 2005, Capitani 2002). The symptoms include loss of motor and/or sensory function in the hand, and the cyclists affected are generally unable to perform daily activities that require dexterity and grip strength. The symptoms may last from several hours to several months (Akuthota 2005).

A review of the literature did not find any papers describing the distribution of pressure on the palm of the hand nor posture of the wrist while riding a road bicycle outdoors on a paved surface. The underlying hypothesis is that current handlebar/grip configurations concentrate the pressure over a relatively small portion of the palm, and this is expected to vary with grip position used. Therefore, the specific aims of the current investigation were:

1. To quantify the distribution of forces across the palms of cyclists as a function of grip position and road grade for handlebars used on road bicycles
2. To quantify the wrist postures adopted as a function of common grip positions used on road biking handlebars

Methods

Experimental Design This study investigated two independent variables, grip position and road grade, for a road bicycle with traditional drop bars. Four levels of grip position, referred to as Top, Hood, Drop, and Flat Drop (Figure 18), were investigated across three
levels of road grade, flat ground, 5% grade downhill, and 5% grade uphill (Figure 19), using a repeated measures design.

Figure 18: Four Levels of Grip Position; (A) Top; (B) Hood; (C) Drop; (D) Flat Drop; (Defined by Akuthota 2005)

Figure 19: Quarter-Mile Long Test Course Showing the Three Levels of Road Grade: Flat Ground, Uphill, and Downhill
In this study, each trial was conducted twice for each grip position resulting in eight trials.

**Participants**

Fourteen experienced cyclists (13 male, 1 female; riding > 10 miles/week) were recruited for this study (µ\text{age} = 24 \text{yr}, σ\text{age} = 3.9\text{yr}; μ\text{height} = 1.80\text{m}, σ\text{height} = 0.046\text{m}; μ\text{weight} = 74.07\text{kg}, σ\text{weight} = 5.44\text{kg}). Participants were required to be between 1.73m and 1.88m tall so that they could be accommodated by the test bicycle which was provided to reduce inter-participant variability.

**Instrumentation**

*Wrist Posture* The wrist posture of each participant was measured for each of the grip positions using two electrogoniometers (Marras and Schoenmarklin 1993). One electrogoniometer, placed on the ulnar side of the right wrist, measured wrist flexion and extension (Figure 20). A second electrogoniometer, placed over the dorsal side of the right wrist, measured the ulnar/radial deviation of the right hand (Figure 21). The measurements of wrist posture were obtained for the four grip positions under static conditions. The test bike was held stationary in a laboratory setting under the assumption that wrist posture is independent of the modest 5% variation in road grade used in this study.
Figure 20: Electrogoniometer Measuring Ulnar (bottom) / Radial (top) Deviation (right image source: badmintoncentral.com)

Figure 21: Electrogoniometer Measuring Flexion (bottom) / Extension (top) of the wrist (right image source: badmintoncentral.com)

*Force Gloves* Each participant wore gloves in which force sensors were mounted on small aluminum discs (9.5mm diameter) and the discs were super-glued to buttons on the palms of thin cloth gloves, as seen in Figure 22. The sensors were calibrated individually using an Instron Machine with three lb increments from zero to fifteen lbs. Calibration
checks were performed before and after every participant was tested by placing a five pound weight on the sensor and verifying consistent readings.

Given the sagittally symmetric nature of the task, six Tekscan FlexiForce A201 Force Sensing Resistors were placed on each hand in a pattern that allowed for a 4 X 3 sensor array when the data were combined from both hands, as seen in Figure 22.

Figure 22: Pressure Sensing Gloves (left); Sensor Positions on the Left Hand when the Data from the Two Gloves are Combined (right)

_Bike Instrumentation_ An accelerometer on the bike indicated where in the data stream the different road grade phases occurred.

Data from each of the sensors were captured using the LabJack® U3HV Data Acquisition System (DAQ) with Azeotech® DAQFactory Express release 5.84 software on a laptop
computer. The laptop computer was held in a backpack worn by the participants along with the DAQ. The laptop battery powered the portable system.

**Procedures**

After signing an informed consent document approved by the Ohio State University IRB, the participant was instrumented with the sensor gloves. Each participant was given as much time as desired to become acquainted with the bicycle and the test course. Once testing began, participants were asked to remain seated and in the same gear throughout the test trials. The gear was selected by the participant with the instructions of pedaling at a comfortable cadence for all three levels of road grade. The participants were asked to stop the bicycle completely in between each of the three road grades for each of the twelve trials. With a complete stop, the vibrations recorded by the accelerometer ceased, and the three road grades could be identified in post processing. In between each trial, the participant was stopped, and the laptop was removed from the backpack without disconnecting any equipment. A new trial was initiated in DAQFactory Express, taking only 20-30 seconds between trials. The sequence of the grip positions for the trials was randomized, and each grip position was repeated once.

Calibration of the sensors was verified between each participant by placing a 2.27kg weight on each sensor before and after each participant was tested to ensure an accurate, repeatable output.
**Data Analysis**

The raw force data were trimmed in MATLAB, removing accelerations, decelerations, and turns during each trial from the processed dataset. The medians of the force values for each portion of the trials (i.e. three road grades) were calculated in order to find the force values when the rider was moving with a constant speed for a given grip and road grade combination. Two test runs were made per condition and the maximum force value during each run was determined for each sensor; the larger value of the two was used as the maximum value for the sensor. This procedure was performed under the assumption that a particular sensor might shift slightly off of the handlebar for a given test run, and such a misreading was not to be included in the data analysis. It was further assumed that this type of shift off one sensor would not influence the readings from the other sensors.

A univariate Analysis of Variance (ANOVA) was used to compare the total normal force on the hand for each grip and grip by road grade combination in SAS 9.2. By looking at the magnitude and location of the forces from each sensor, the relative localization of pressure was found.

The flexion/extension and ulnar/radial deviation describing postures of the wrist for each grip position were compared using a univariate ANOVA in SAS 9.2.
Results

Forces on the Palm. The ANOVA of the force data showed that the total normal force on the hand was significantly affected by the type of grip (p < 0.001). The 5% positive and negative change in road grade did not significantly affect the total force, nor was there an interaction between grip and road grade. Figure 23 shows that there was greater total force for both the top and drop grips. Relative to these grip positions, the total force was reduced for the hood and flat drop grips. Significant differences were determined using the REGWQ Post-Hoc test in SAS. The normal force values are quite low, 9 to 16N, but these low values were confirmed with a hand dynamometer test in the lab, simulating the postures adapted for the grip positions.
Figure 23: Total Force on One Hand for Each Grip Position (Standard Error Bars Shown; Mean Rider Weight: 74 kg; REGWQ Horizontal Grouping Bars indicate Non-Significant Difference)

The sensors were analyzed individually for the percentage of the load carried on average. Table 2 reports the mean percentage of the load carried by each of the sensors, collapsed across participants and road grades.
Table 2: Mean Percentage of Load Carried by Each Sensor (Shaded Cells ≥ 10%)

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Top Grip</th>
<th>Hood Grip</th>
<th>Drop Grip</th>
<th>Flat Drop Grip</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4%</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
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<td>2</td>
<td>10%</td>
<td>1%</td>
<td>7%</td>
<td>10%</td>
</tr>
<tr>
<td>3</td>
<td>11%</td>
<td>11%</td>
<td>7%</td>
<td>21%</td>
</tr>
<tr>
<td>4</td>
<td>4%</td>
<td>1%</td>
<td>34%</td>
<td>25%</td>
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<td>5%</td>
<td>33%</td>
<td>6%</td>
<td>2%</td>
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<td>0%</td>
<td>11%</td>
<td>1%</td>
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<td>23%</td>
<td>23%</td>
<td>7%</td>
<td>15%</td>
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<td>26%</td>
<td>10%</td>
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<td>12%</td>
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<td>16%</td>
<td>1%</td>
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<td>1%</td>
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<td>4%</td>
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<td>1%</td>
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<td>0%</td>
<td>1%</td>
<td>18%</td>
<td>1%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Figure 24 is a visual representation of the above table. In the figure, the number above each sensor represents the mean percentage of the load that the individual sensor carries for a particular grip. The actual sensor number scheme is given by a subscript value, ex. S2 for sensor 2. It can be seen that the Top and Flat Drop Grip positions recorded the force distribution primarily across the middle of the palm. The Hood Grip recorded most of the force across the fleshy region of the palm at the base of the thumb, and the Drop Grip recorded most of the force over the hypothenar eminence under the fifth digit.
Figure 24: Mean Percentage of Load Carried by Each Sensor (Shaded Cells ≥ 10%; Hand Image: Capitani 2002)
**Wrist Posture.** Figure 25 shows the amount of extension and ulnar/radial deviation in the wrist for each grip position (extension p < 0.0001, ulnar deviation p < 0.0001). It can be seen that the Drop Grip recorded the highest amount of extension, 30.5°, with the Top Grip and Flat Drop Grips following closely, 26.4° and 24.0° of extension respectively. The Hood Grip recorded the most neutral wrist posture in regards to extension, 15.9°.

![Figure 25: Median Wrist Extension and Ulnar Deviation for Mountain Bike Grip Positions](source: badmintoncentral.com)

Figure 25 also shows that significant differences were seen across the four grip positions in regards to ulnar and radial deviation. The Drop Grip showed the highest ulnar deviation, 28.5°, followed by the Top Grip with 9.9° of ulnar deviation. The Hood Grip and Flat Drop Grips had relatively neutral posture in regards to ulnar/radial deviation.
Discussion

Grip position had a significant effect on the total force on the hand, the force distribution on the palm of the hand, and the posture of the wrist. There was no effect due to the 5% road grade either directly or via a road grade by grip interaction. When looking at the average percentage of the load carried by each of the individual sensors, i.e. the results presented in Table 2, over 83% of the total load for each grip position was carried by only five of the sensors. In addition, each grip position had at least one sensor that carried over 25% of the total load. This suggests that the current handlebar design does not distribute the pressure on the palm of the hand effectively.

The highest total force on the hand was observed in the Top Grip position. Although the rider is in a more hunched, aerodynamic stance on the bicycle in the two drop positions, it was observed that riders tended to lock or nearly lock their elbows in the Top Grip Position. This indicates that the riders tended to lean on the bar more in the Top position, as compared to the other positions. In addition, the forces transmitted to the bar from the hands are more perpendicular to the bar in the Top Grip position as compared to the Hoods and Drops. In the Hoods and Drops, riders hold the bar in a fashion that relies more heavily on shear forces rather than direct, nearly vertical contact. By this logic, one might expect the Flat Drop position to have as high if not higher forces than the Top Grip position. However, the hands are much closer together in the Top Grip position as compared to the Flat Drop Grip position, thus riders have less leverage and balance in the Top position. This requires riders to gain leverage by squeezing the bar to stabilize their
upper bodies. This trend might not be observed with professional riders, as their ability to balance may negate the need to squeeze the bar. These results are supported by a study by Potter et al. (2008) that reported the total force on the saddle increases by roughly 10 kPa (∼9%) when a rider switches from the Top to the Drop position.

Figure 24 showed that the Top Grip distributes pressure across the middle of the palm, above the median nerve and the motor branch of the ulnar nerve. This suggests that the Top Grip may result in symptoms of Carpal Tunnel Syndrome and loss of motor function of the ulnar intrinsic muscles. The Hood Grip recorded pressure across the fleshy portion of the palm, primarily above the median nerve, which could contribute to the development of symptoms of Carpal Tunnel Syndrome. The Drop Grip presented the poorest distribution of pressure, as Sensor 4 recorded 34% of the total force on the hand on average. This location is directly above the ulnar nerve, and may compress the motor and/or sensory branch of the ulnar nerve, given the size of the participant’s hands. This suggests that the Drop Grip may result in loss of motor function of the ulnar intrinsic muscles and/or sensory function on the ulnar side of the hand. The Flat Drop Grip recorded pressure across the middle of the palm, suggesting that this grip could contribute to the same symptoms as with the Top Grip position.

When looking at the posture of the wrist, it is evident that the Drop Grip position is most problematic. It recorded the highest extension (30.5°) and radial deviation (28.5°). Keir (2007) found that the angles of the wrist that protect 75% of the study population from a
30mmHg critical pressure in the carpal tunnel were 32.7° for extension and 21.8° for radial deviation. This suggests that the Drop Grip position is not only at a high risk for all types of Handlebar Palsy, but also for symptoms of Carpal Tunnel Syndrome.

Slane et al. (2010) found that the peak pressures on the palm increase for the Drop position as compared to the Top position. The study was performed using a pressure mat, rather than individual sensors. This identifies the limitation of using individual force sensors, as used in this study, as some of the forces may be transmitted through non-sensing areas. The use of individual sensors rather than a pressure pad was decided upon based on a study by Kong (2005). Kong used the same TekScan FlexiForce sensors to evaluate optimal torque tool handle diameters. For the current study, the individual sensors were elevated to create discrete contact points, but there was still buckling of the glove’s palm between sensors. Further limitations of the current study include the limited sample size, fourteen participants, and the small road grade, 5%. The 5% road grade may not be enough to measure differences in total force and force distribution on the palm, but differences may exist for larger hills.

**Conclusion**

It was found that the Drop Grip position resulted in the second highest total normal force on the hand, the poorest distribution of pressure on the palm, and the largest amount of wrist extension and ulnar deviation. This suggests that the Drop Grip position is maybe the most problematic grip position for avoiding symptoms of handlebar palsy.
This study may be used to guide the design of road bike handlebars. The study showed that the current, traditional bend drop bars that are typically used on road bicycles are not efficient at evenly distributing the pressure on the palm of the hand. This is likely the reason for the 92% incidence of motor and/or sensory disturbances found by Patterson 2003 and Akuthota 2005.
Chapter 5: Localized Hand Pressures when Riding a Mountain Bike: The Effects of Grip Position and Road Grade

Abstract
A neuropathy known as handlebar palsy develops when a lesion of the ulnar nerve takes place due to cyclists concentrating the weight of their upper body on their hands while their hands grasp the handlebars of a bicycle (Akuthota 2005, Patterson 2003). The objective of this study was to identify the magnitudes and locations of the forces on the palms of the hands of 11 mountain cyclists, while also measuring wrist posture. While riding, participants wore force sensing gloves that were connected to a portable data acquisition system. The study investigated two mountain bike grip positions and three road grades. Grip position significantly affected the total force on the hand, the force distribution across the hand, and the posture of the wrist, independently of road grade. These data can be used to guide the design of handlebars that would more evenly distribute the pressure on the palm of the hand.

Introduction
Handlebar palsy, also known as "cyclist palsy", is a nerve condition caused by the compression of the ulnar nerve in the palm of the hand while riding a bicycle (Akuthota 2005). It develops from riders bearing their upper body weight on their palms while
gripping the handlebar, and it is associated with road cycling, as well as mountain biking (Capitani 2002, Patterson 2003). Handlebar Palsy affects both competitive and recreational cyclists, and the symptoms are dependent on the location and severity of the nerve lesion (Akuthota 2005, Capitani 2002). The symptoms include loss of motor and/or sensory function in the hand, and the cyclists affected are generally unable to perform daily activities that require dexterity and grip strength. The symptoms may last from several hours to several months (Akuthota 2005).

A review of the literature did not find any papers describing the distribution of pressure on the palm of the hand nor posture of the wrist while riding a mountain bike outdoors. The underlying hypothesis is that current handlebar/grip configurations concentrate the pressure over a relatively small portion of the palm, and this is expected to vary with grip position used. Therefore, the specific aims of the current investigation were:

1. To quantify the distribution of forces across the palms of cyclists as a function of grip position and road grade for handlebars used on mountain bicycles
2. To quantify the wrist postures adopted as a function of common grip positions used on mountain biking handlebars

Methods

Experimental Design This study investigated two independent variables, grip position and road grade, for a mountain bicycle with traditional riser bars. Two levels of grip position, referred to as Main and Climb (Figure 26), were investigated across three levels
of road grade, flat ground, 5% grade downhill, and 5% grade uphill (Figure 27), using a repeated measures design.

Figure 26: Two Levels of Grip Position; (A) Main; (B) Climb; (Defined by Capitani and Beer 2002)

Figure 27: Quarter-Mile Long Test Course Showing the Three Levels of Road Grade: Flat Ground, Uphill, and Downhill
In this study, each trial was conducted twice for each grip position resulting in eight trials.

**Participants**

Fourteen experienced cyclists (13 male, 1 female; riding > 10 miles/week) were recruited for this study ($\mu_{\text{age}} = 25.1\text{yr}, \sigma_{\text{age}} = 4.0\text{yr}; \mu_{\text{height}} = 1.8\text{m}, \sigma_{\text{height}} = 0.051\text{m}; \mu_{\text{weight}} = 73.6\text{kg}, \sigma_{\text{weight}} = 5.44\text{kg}$). Participants were required to be between 1.73m and 1.88m tall so that they could be accommodated by the test bicycle which was provided to reduce inter-participant variability.

**Instrumentation**

*Wrist Posture* The wrist posture of each participant was measured for each of the grip positions using two electrogoniometers (Marras and Schoenmarklin 1993). One electrogoniometer, placed on the ulnar side of the right wrist, measured wrist flexion and extension (Figure 28). A second electrogoniometer, placed over the dorsal side of the right wrist, measured the ulnar/radial deviation of the right hand (Figure 29). The measurements of wrist posture were obtained for the four grip positions under static conditions. The test bike was held stationary in a laboratory setting under the assumption that wrist posture is independent of the modest 5% variation in road grade used in this study.
Force Gloves Each participant wore gloves in which force sensors were mounted on small aluminum discs (9.5mm diameter) and the discs were super-glued to buttons on the palms of thin cloth gloves, as seen in Figure 30. The sensors were calibrated individually using an Instron Machine with three lb increments from zero to fifteen lbs. Calibration
checks were performed before and after every participant was tested by placing a five pound weight on the sensor and verifying consistent readings.

Given the sagittally symmetric nature of the task, six Tekscan FlexiForce A201 Force Sensing Resistors were placed on each hand in a pattern that allowed for a 4 X 3 sensor array when the data were combined from both hands, as seen in Figure 30.

Figure 30: Pressure Sensing Gloves (left); Sensor Positions on the Left Hand when the Data from the Two Gloves are Combined (right)

_Bike Instrumentation_ An accelerometer on the bike indicated where in the data stream the different road grade phases occurred.

Data from each of the sensors were captured using the LabJack© U3HV Data Acquisition System (DAQ) with Azeotech® DAQFactory Express release 5.84 software on a laptop
computer. The laptop computer was held in a backpack worn by the participants along with the DAQ. The laptop battery powered the portable system.

**Procedures**

After signing an informed consent document approved by the Ohio State University IRB, the participant was instrumented with the sensor gloves. Each participant was given as much time as desired to become acquainted with the bicycle and the test course. Once testing began, participants were asked to remain seated and in the same gear throughout the test trials. The gear was selected by the participant with the instructions of pedaling at a comfortable cadence for all three levels of road grade. The participants were asked to stop the bicycle completely in between each of the three road grades for each of the twelve trials. With a complete stop, the vibrations recorded by the accelerometer ceased, and the three road grades could be identified in post processing. In between each trial, the participant was stopped, and the laptop was removed from the backpack without disconnecting any equipment. A new trial was initiated in DAQFactory Express, taking only 20-30 seconds between trials. The sequence of the grip positions for the trials was randomized.

Calibration of the sensors was verified between each participant by placing a 2.27kg weight on each sensor before and after each participant was tested to ensure an accurate, repeatable output.
Data Analysis

The raw force data were trimmed in MATLAB, removing accelerations, decelerations, and turns during each trial from the processed dataset. The medians of the force values for each portion of the trials (i.e. three road grades) were calculated in order to find the force values when the rider was moving with a constant speed for a given grip and road grade combination. Being as there were two test runs per condition, the maximum force values between the two runs were taken for each sensor. This was performed under the assumption that a particular sensor might shift slightly off of the handlebar for one of the two test runs. It was assumed that if this shift of one sensor happened, the other sensors wouldn’t necessarily read higher values because they might not have shifted at all during the two runs. Therefore, the maximum of the two readings was taken.

A univariate Analysis of Variance (ANOVA) was used to compare the total normal force on the hand for each grip and grip by road grade combination in SAS 9.2. By looking at the magnitude and location of the forces from each sensor, the relative localization of pressure was found.

The flexion/extension and ulnar/radial deviation describing postures of the wrist for each grip position were compared using a univariate ANOVA in SAS 9.2.

Results

Forces on the Palm. The ANOVA of the force data showed that the total force on the hand was significantly higher with the climbing grip than with the main grip (p < 0.001).
The 5% positive and negative change in road grade did not significantly affect the total force, nor was there an interaction between grip and road grade. Figure 31 shows that there was greater total force for the Climb Grip compared to the Main Grip.

![Mean Total Force on One Hand for Mountain Bike Grip Positions](image)

Figure 31: Total Force on One Hand for Each Grip Position (Standard Error Bars Shown)

The sensors were analyzed individually for the percentage of the load carried on average. Table 3 reports the mean percentage of the load carried by each of the sensors, collapsed across participants and road grades.
Table 3: Mean Percentage of Load Carried by Each Sensor (Gray Cells >10%)

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Main Grip</th>
<th>Climb Grip</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2%</td>
<td>0%</td>
</tr>
<tr>
<td>2</td>
<td>10%</td>
<td>3%</td>
</tr>
<tr>
<td>3</td>
<td>6%</td>
<td>11%</td>
</tr>
<tr>
<td>4</td>
<td>16%</td>
<td>15%</td>
</tr>
<tr>
<td>5</td>
<td>6%</td>
<td>4%</td>
</tr>
<tr>
<td>6</td>
<td>0%</td>
<td>3%</td>
</tr>
<tr>
<td>7</td>
<td>32%</td>
<td>21%</td>
</tr>
<tr>
<td>8</td>
<td>16%</td>
<td>28%</td>
</tr>
<tr>
<td>9</td>
<td>10%</td>
<td>7%</td>
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<tr>
<td>10</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>11</td>
<td>0%</td>
<td>5%</td>
</tr>
<tr>
<td>12</td>
<td>0%</td>
<td>3%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Figure 32 is a visual representation of the above table. In the figure, the number above each sensor represents the mean percentage of the load that individual sensor carries for a particular grip. The actual sensor number scheme is given by a subscript value, ex. S2 for sensor 2. It can be seen that the forces are distributed across the middle of the palm for both grip positions.
Figure 32: Mean Percentage of Load Carried by Each Sensor (Gray Cells > 10%; Hand Image: Capitani 2002)

**Wrist Posture.** Figure 33 shows the amount of extension and ulnar deviation in the wrist for the two grip positions (extension $p < 0.0001$, ulnar deviation $p < 0.0001$). The Climbing Grip showed higher extension ($27.4{}^\circ$) than the Main Grip ($18{}^\circ$), but showed less ($4.6{}^\circ$) than the Main Grip ($11.9{}^\circ$).
Discussion

Grip position had a significant effect on the total force on the hand, the force distribution on the palm of the hand, and the posture of the wrist. There was no effect due to the 5% road grade either directly or via a road grade by grip interaction. When looking at the average percentage of the load carried by each of the individual sensors (i.e. the results presented in Table 3, over 80% of the total load for each grip position was distributed across only five of the sensors. In addition, each grip position had at least one sensor, albeit different across grips, that carried over 25% of the total load. These findings suggest that a standard mountain bike riser bar with bar ends for climbing does not distribute the pressure on the palm of the hand effectively.

Figure 33: Wrist Extension and Ulnar/Radial Deviation for a Given Grip Position (inset image source: badmintoncentral.com)
The highest total normal force on the hand was observed in the Climb Grip position. The main reason for this is that bar ends are traditionally left unpadded, and were therefore not padded for testing. This increases the total measured force on the hand, as the grip does not dampen the forces being transmitted to the force gloves. The lack of padding also results in a smaller diameter grip, thus concentrating the large forces over a smaller area of the palm. In addition, riders tended to lock or nearly lock their elbows in the Climb Grip Position. This may result in more body weight being transferred through the palms, as riders tended to lean on the bar more in this position, as compared to the Main position.

Figure 32 showed that both grip positions distribute pressure across the middle of the palm, above the median nerve and the motor branch of the ulnar nerve. This suggests that both positions may contribute to the development of symptoms of Carpal Tunnel Syndrome and loss of motor function of the ulnar intrinsic muscles. However, it is evident that more of the palm could be used to distribute the pressure. This distribution of forces is consistent with the distribution of pressure across the palm found by Slane (2010). Slane tested for the pressure distribution as a function of glove material using a pressure pad that covered most of the palm above the lower, ulnar side. When comparing the current study to the data from Slane’s control group, i.e. without gloves, both studies found large peak pressures across the mid-section of the palm.
The distribution of pressure across the palm, although not reported extensively in the reviewed literature, has been a recent topic within the cycling industry. One company, Ergon (http://www.ergon-bike.com), has addressed this concern by creating an aftermarket grip that attaches to any standard mountain bike handlebar. The grips offer a larger palmar surface area, while allowing the rider to adjust the required amount of wrist extension needed to grasp the bar. An example Ergon grip, seen in Figure 34 below, has won numerous biking and ergonomics design awards.

When looking at the posture of the wrist, it is evident that the Climb Grip position is most problematic in terms of extension (27.4°). Keir (2007) found that the angles of the wrist that protect 75% of the study population from a 30mmHg critical pressure in the carpal tunnel were 32.7° for extension. This suggests that the Climb Grip position is not only at a high risk for Type II and Type III Handlebar Palsy, but also for symptoms of Carpal Tunnel Syndrome.
Conclusion

It was found that the Climb Grip position resulted in a higher total force on the hand and more extension of the wrist when compared to the Main Grip position. The higher measured forces were due to the lack of padding, as bar ends are traditionally left unpadded by mountain bikers. This study shows that factors such as grip cross section and padding have a significant effect on total force on the hand and amount of wrist extension. Both grips distributed the forces across the midsection of the palm, above the median nerve and the motor branch of the ulnar nerve. Therefore, the current grip positions offered on traditional riser bars on mountain bikes are likely to contribute to symptoms of carpal tunnel syndrome or Handlebar Palsy of the motor disturbances type, consistent with Patterson’s findings (2003).
Chapter 6: Design of an Experimental Grip for the Drop Grip Position on Traditional Road Bike Handlebars

Abstract

A neuropathy known as handlebar palsy develops when a lesion of the ulnar nerve takes place due to cyclists concentrating the weight of their upper body on their hands while their hands grasp the handlebars of a bicycle (Akuthota 2005, Patterson 2003). Previous findings (Chapter 4) identified the Drop Grip position as the most problematic grip on road bike handlebars in terms of force distribution, flexion, and radial deviation. The objective of this study was to identify how wrist posture and the magnitude and locations of the forces on the palms of the hands while in the Drop Grip position on a road bike could be impacted by variations in handlebar design. A single participant was instrumented with force sensing gloves and a portable data acquisition system. This study found that the total force on the hand is distributed more evenly for a customized grip, and decreased for a handlebar that was wrapped twice with bar tape.

Introduction

Handlebar palsy, also known as "cyclist palsy", is a nerve condition caused by the compression of the ulnar nerve in the palm of the hand while riding a bicycle (Akuthota 2005). It develops from riders bearing their upper body weight on their palms while
gripping the handlebar, and it is associated with road cycling as well as mountain biking (Capitani 2002, Patterson 2003). Handlebar Palsy affects both competitive and recreational cyclists, and the symptoms are dependent on the location and severity of the nerve lesion (Akuthota 2005, Capitani 2002). The symptoms include loss of motor and/or sensory function in the hand, and those that are affected are generally unable to perform daily activities that require dexterity and grip strength. The symptoms may last from several hours to several months (Akuthota 2005).

A review of the literature did not find any papers describing the distribution of pressure on the palm and posture of the wrist for experimental grip shapes for bicycle handlebars. The goal of this study is to determine if the pressure distribution on the palm, and the flexion and radial deviation of the wrist, can be improved through an experimental grip for the Drop Grip position on a road bike. Specifically, the aims of this pilot investigation were:

1. To quantify the distribution of forces across the palms as a function of experimental grip shape in the Drop Grip position on a road bike
2. To quantify the wrist postures adopted as a function of the experimental grip positions

**Methods**

*Experimental Design* This study investigated one independent variable, grip shape, for a Drop Grip position on a road bike. Four experimental grip shapes were investigated, using a repeated measures design for one pilot subject. The subject rode on a set of Cyclops Rollers, simulating actual riding conditions in a laboratory environment. The
first tested grip was considered the control, as it was a standard drop bar wrapped with padded bar tape (Figure 35). The padded bar tape used for two of the grips was PRO Handlebar Tape. The second tested grip was wrapped twice with padded bar tape (Figure 36). The third grip was a customized, plastic grip was created using ShapeLock™ material (Figure 37). After the third grip was tested, it was modified to alter the force distribution across the palm of the hand, and became the fourth tested grip (Figure 38). The modification smoothed out the grip under the ulnar nerve, removing a “ridge” that was originally created by squeezing the moldable plastic to the bar. This “ridge” can be seen in Figure 38 and the smoothed out grip can be seen in Figure 39.

Figure 35: First of the Four Experimental Grip Positions on the Road Bike - Single Wrapped Bar in Bent portion of Drop Bar
Figure 36: Second of the Four Experimental Grip Positions on the Road Bike - Double Wrapped Bar in Bent portion of Drop Bar

Figure 37: Third of the Four Experimental Grip Positions on the Road Bike – Molded Drop Grip Created Using ShapeLock (Arrow Indicates “Ridge” on Grip)
Figure 38: Fourth of the Four Experimental Grip Positions on the Road Bike – Molded, Modified Drop Grip Created Using ShapeLock (Arrow Indicates Smoothed Grip)

Participants

The one participant for this pilot study was the author (Age = 25, Weight = 68 kg, Height = 1.73m).

Apparatus and Instrumentation

Bicycle and Handlebars The bicycle used for testing was a 54cm Motobecane Track Bike. The custom, molded grips were made from two hundred grams of ShapeLock plastic per grip. The material was melted down using hot water before being shaped to the one participant’s hands.

Instrumentation for Measuring Wrist Posture The wrist posture of the participant was measured for each of the grip positions using two electrogoniometers (Marras and Schoenmarklin 1993). One electrogoniometer, placed on the ulnar side of the right wrist, measured wrist flexion and extension (Figure 39). A second electrogoniometer, placed
over the dorsal side of the right wrist, measured the ulnar/radial deviation of the right hand (Figure 40). The measurements of wrist posture were obtained for the experimental grip positions on the rollers, simulating actual riding on flat ground.

Figure 39: Electrogoniometer Measuring Ulnar (bottom) / Radial (top) Deviation (right image source: badmintoncentral.com)

Figure 40: Electrogoniometer Measuring Flexion (bottom) / Extension (top) of the wrist (right image source: badmintoncentral.com)
**Force Gloves** The participant wore gloves in which force sensors were mounted on small aluminum discs (9.5mm diameter) and the discs were super-glued to buttons on the palms of thin cloth gloves, as seen in Figure 41. The sensors were calibrated individually using an Instron Machine with three lb increments from zero to fifteen lbs. Calibration checks were performed before and after every participant was tested by placing a five pound weight on the sensor and verifying consistent readings.

Given the sagittally symmetric nature of the task, six Tekscan FlexiForce A201 Force Sensing Resistors were placed on each hand in a pattern that allowed for a 4 X 3 sensor array when the data were combined from both hands, as seen in Figure 41.

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![Figure 41: Pressure Sensing Gloves (left); Sensor Positions on the Left Hand when the Data from the Two Gloves are Combined (right)](image-url)
Data from each of the sensors were captured using the LabJack© U3HV Data Acquisition System (DAQ) with Azeotech® DAQFactory Express release 5.84 software on a laptop computer. The laptop battery powered the portable system.

**Procedures**

The participant was instrumented with the sensor gloves. Once testing began, the participant remained seated throughout the test trials. The cadence was kept constant by riding in the bicycle’s one gear between 18-19 mph. The speed was identified by the wireless bike computer. The participant performed eight trials for each grip position. In between each trial, the participant continued riding without placing any weight on the handlebar. The gaps in the force readings therefore identified the eight trials per grip in post processing. The handlebar was swapped out for each grip position, as each of the eight trials per grip were performed consecutively.

**Data Analysis**

The raw force data were trimmed to eliminate the forces due to settling into the grip position. The medians of the force values for each of the trials were calculated in order to find the force values for a given experimental grip position. The wrist posture data were visually inspected for trends between the four experimental grips.

The force data was analyzed for total normal force on the hand and the force distribution on the palm, as a function of experimental grip shape. Statistical analyses were not performed given the observations were limited to a single subject.
Results

Wrist Posture  Figure 42 shows the results of the wrist posture for three of the experimental grip conditions. The modification to the Custom Molded Grip, which created the fourth experimental grip, did not have any effect on wrist posture, as the only change to the grip was the removal of the “ridge”. It can be seen in Figure 42 that extension is largest for the double wrapped bar and for the experimental grip. These grip shapes provide a larger palmer area towards the rider, which in turn increases the amount of extension in the wrist. It can also be seen that radial deviation was least for the custom molded grip. This was because the Custom Molded Grip sat lower in the bent portion of the drop bar than the curved area that was grabbed by the subject for the single and double wrapped handlebars (first and second experimental grips). This can be seen in Figures 38 and 39.

Figure 42: Extension in the Wrist as a Function of Experimental Grip
**Force Data** Although there were large amounts of variability in the force data, there were still observable trends between the four grip conditions. Figure 43 shows the total force on the hand for each of the grip shapes.

![Median Total Force on One Hand for Experimental Drop Grips](image)

Figure 43: Total Force on One Hand for Each of the Experimental Drop Grips

The total force on the hand was smallest for the double wrapped bar. The total force on the hand was largest for the two custom grips, and the single wrapped handlebar had a total force value in between the double wrapped bar and the custom grips.

Table 4 summarizes the median percentage of the load carried by each of the sensors for each of the grip conditions.
Table 4: Mean Percentage of Load Carried by Each Sensor with Standard Deviation Shown (Gray cells Mean>10% and SD>0.1)

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Single Wrapped Bar</th>
<th>Double Wrapped Bar</th>
<th>Custom Grip</th>
<th>Custom Grip Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean % Load</td>
<td>SD</td>
<td>Mean % Load</td>
<td>SD</td>
</tr>
<tr>
<td>1</td>
<td>7%</td>
<td>0.00</td>
<td>2%</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>3%</td>
<td>0.07</td>
<td>6%</td>
<td>0.11</td>
</tr>
<tr>
<td>3</td>
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<td>3%</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
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<td>5</td>
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<td>11</td>
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</tr>
<tr>
<td>Total/AVG.</td>
<td>100%</td>
<td>0.07</td>
<td>100%</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 4 shows that for the Single Wrapped Bar, the load is distributed primarily across four sensors 1, 3, 4, and 7, with number 4 showing the largest pressure. For the Double Wrapped Bar, 45% of the load is carried by sensor 4. For the first Custom, Molded Grip, sensors 3 and 4 carried a total of 55% of the load. For the Modified, Custom Grip, the load was distributed across sensors 1, 3, 4, and 12 with 13-21% per sensor.

**Discussion**

These results are to be taken with caution, as only one participant, the author, was analyzed, and there was a considerable amount of inter-trial variation, as given by the standard deviations of Table 4. However, there were distinct trends that were observed even with the large deviations. When looking at the wrist posture data, it was found that
larger and flatter grips tend to increase the amount of extension in the wrist, while the amount of radial deviation is not largely affected. The reason for the increased extension is that the upper body weight of the subject is supported by more direct, normal contact with the palm, rather than shear force as with the standard bar.

It was found that double wrapping the handle bar reduces the total measured normal force on the hand. This makes sense as the forces transmitted from the bar to the hand are damped by the additional layer of padding and the surface area exposed to the palm is increased. It can be seen that the Double Wrapped bar distributes the total force well with the exception of the location of sensor 4. This is most likely due to the fact that the extra layer of bar tape reduced the size of the gap in the curved portion of the drop bar. This created a large pressure point at sensor 4, and therefore 55% of the load was carried by this location.

While the surface area exposed to the palm was even greater for custom grip conditions, the total force is much higher for the custom grips. This likely resulted because there was no padding on the custom grips, and therefore there was no dampening of the forces. The modified custom grip condition showed a reduction in the total hand force relative to the original custom grip position by removing the “ridge” created in the molding process. This modification reduced the force in sensor 4, the sensor directly above the ulnar nerve, by nearly 50 percent. When comparing the Single Wrapped Bar to the Custom Modified Grip, there seems to be no glaring advantage of the customized grip. The percentage of
the load carried by sensors 3, 4, 7, and 9 are reduced, but the percentage of the load
carried by sensors 1 and 12 increased significantly.

The inconsistencies in the data were thought to be removed by taking the mean value for
each of the sensors for each of the eight trials per grip. It can be seen in the standard
deviations columns of Table 4 that the sensors that often recorded the highest forces also
had the most deviation. This is another reason to take the results with caution. The most
likely reason for the inconsistent result was that the force gloves were in poor condition
from the prior study. Many of the “tail ends” of the force sensors (i.e. the plastic, non-
sensing area), were creased due to the number of occurrences of participants placing
weight on the gloves without ensuring that the sensors were in fact flat. This may have
interfered with the voltage output of the sensor, even though the sensing area was intact.

In prior testing, the sensing area of sensors sometimes slipped off of the aluminum disk
that they were attached to. This required super gluing the sensor back onto the disk.
However, it was unrecognized that any superglue that made contact with the synthetic
leather palm of the glove was actually degrading the material. This caused some of the
sensors to sit unevenly on the glove, rather than resting perfectly flat. This was an issue
because the buttons that the aluminum disks were glued to often became loose from
subjects twisting their grip on the bar. This caused the buttons to extend from the palm,
loosening the attachment threads, and requiring the use of superglue if the detachment
occurred in mid-test.
When looking at the posture of the wrist, it is evident that the double wrapped bar and the custom, molded grip positions are most problematic in terms of extension, 37° and 46°, respectively. Keir (2007) found that the angles of the wrist that protect 75% of the study population from a 30mmHg critical pressure in the carpal tunnel were 32.7° for extension. This suggests that the these two grip positions are not only at risk for Type II and Type III Handlebar Palsy, but they are also at an extremely high risk for symptoms of Carpal Tunnel Syndrome. Even the standard, single wrapped bar is at a high risk, as supported by Chapter 4 results.

**Conclusion**

The results of this study are to be taken with caution due to its use of a single subject and the inter-trial variability in the measure. It was shown that for the Drop Grip Position, the total force on the hand and the force distribution on the palm is affected by the shape of the grip. An additional layer of bar tape was shown to reduce the total measured normal force on the hand. Although not supported by the data, a custom, molded grip is believed to distribute the pressure on the palm of the hand, as subjective comments by the author suggest that the experimental grip made from ShapeLock was the most comfortable grip tested. This subjective result can be used to direct the shape of future experimental grips. In addition, a result such as this proposes the concept that a package of ShapeLock or similar material could be sold at bike shops to provide riders with the option to create customizable grips for the existing handlebars on their bike.
Chapter 7: Conclusion

Handlebar palsy, also known as "cyclist palsy", is a nerve condition caused by the compression of the ulnar nerve in the palm of the hand while riding a bicycle (Akuthota 2005). It develops from riders bearing their upper body weight on their palms while gripping the handlebar, and it is associated with road cycling, as well as mountain biking (Capitani 2002, Patterson 2003). Handlebar Palsy affects both competitive and recreational cyclists, and the symptoms are dependent on the location and severity of the nerve lesion (Akuthota 2005, Capitani 2002). The symptoms include loss of motor and/or sensory function in the hand, and the cyclists affected are generally unable to perform daily activities that require dexterity and grip strength. The symptoms may last from several hours to several months (Akuthota 2005).

A review of the literature revealed that Handlebar Palsy is indeed a serious injury, but there has not been much work done to quantify and locate the forces on the palms of the hands of cyclists. Therefore, the current study was undertaken to determine the posture of the wrist and the pressure distribution on the palms of the hands of road and mountain cyclists. The primary objectives and finding of study were:
1. **To quantify the distribution of forces across the palms of cyclists as a function of grip position and road grade for handlebars used on road and mountain bicycles**

Road Bike Findings:

I. Grip position had a significant effect on the total force on the hand and the force distribution on the palm of the hand.

II. There was no effect due to the 5% road grade either directly or via a road grade by grip interaction.

III. The highest total force on the hand was observed in the Top Grip position.

IV. The Drop Grip position resulted in the second highest total force on the hand and the poorest distribution of pressure on the palm.

Mountain Bike Findings:

I. Grip position had a significant effect on the total force on the hand and the force distribution on the palm of the hand.

II. The highest measured total force on the hand was observed in the Climb Grip position. The main reason for this is that the Climb Grip is traditionally left unpadded, and was therefore not padded for testing.

III. Both grip positions distribute pressure across the middle of the palm, above the median nerve and the motor branch of the ulnar nerve. This suggests that both positions may result in symptoms of Carpal Tunnel Syndrome and loss of motor function of the ulnar intrinsic muscles.
2. To quantify the wrist postures adopted as a function of common grip positions used on road biking and mountain biking handlebars

Road Bike Findings:
I. Grip position had a significant effect on the posture of the wrist.
II. There was no effect due to the 5% road grade either directly or via a road grade by grip interaction.
III. The Drop Grip position resulted in the largest amount of wrist extension and ulnar deviation.

Mountain Bike Findings:
I. Grip position had a significant effect on the posture of the wrist. The Climb Grip position resulted in more extension of the wrist when compared to the Main Grip position
II. There was no effect due to the 5% road grade either directly or via a road grade by grip interaction.

3. To pilot whether or not the distribution of forces across the palms could potentially be altered through modifications in design of the drop grip on road bicycles.
I. The double wrapped handlebar reduced the total measured normal force on the hand.
4. To pilot how the wrist postures would be altered through modifications in handlebar grip design.

I. Grip shapes that provide a larger, palmar surface area increased the amount of extension in the wrist.

The above findings suggest that the Drop Grip position on a road bike is the most problematic grip position for avoiding symptoms of handlebar palsy. The study showed that the current, traditional bend drop bars that are typically used on road bicycles are not efficient at evenly distributing the pressure on the palm of the hand. This is likely the reason for the 92% incidence of motor and/or sensory disturbances found by Patterson 2003 and Akuthota 2005.

The higher forces in the Climb Grip of a mountain bike were due to lack of padding, as this grip position is traditionally left unpadded by mountain bikers. This study shows that padding has a significant effect on total force measured on the hand. Both grips, the main grip and climbing grip, distributed the forces across the midsection of the palm, above the median nerve and the motor branch of the ulnar nerve. Therefore, the current grip positions offered on traditional riser bars on mountain bikes are likely to result in carpal tunnel syndrome or Handlebar Palsy of the motor disturbances type, as consistent with Patterson 2003.
When looking at the results of the design study, it was found that bar tape reduced the total force on the hand, and a custom, molded grip may be used to distribute the pressure on the palm of the hand more evenly.

Limitations of the performed tests were mostly due to the test equipment. Due to the equipment, collection of the total force on the palm of the hand was limited to twelve data points. Had a pressure pad been utilized, the number of data points would have increased, providing for a much more refined mapping of the forces on the palm of the hand. In addition, the pressure mat would have one calibration curve, rather than the twelve individual calibration curves of the utilized force gloves. The individual force sensors also left sizable gaps on the palm where forces could be transmitted from the upper body to the handlebar. However, the sensors were elevated on the glove, creating more defined contact points. The drawback of this design, however, is that sometimes the palm between sensors would buckle. This causes shifting of the sensors on the palm, and sometimes caused sensors to move off of the handlebar that would ordinarily be in contact with the bar. The elevated sensors may have also created discomfort for the participants as they gripped the bar, although this was never reported by a participant.

Limitations other than test equipment included the small grade of the hill used for testing, 5%. Had a larger grade hill been used, the force distribution may have been affected. This is hypothesized based on the fact that riders tend to pull up on the handlebars when riding up a steep hill.
Future studies would benefit from the use of a pressure mat due to the fact that the consistency of results between the right and left hands could be measured. With the current study, the sensors were offset between hands to create a four by three grid of sensors on one palm, assuming sagittal symmetry. However, this does not allow for variability checks between hands. Future studies should also investigate stops and starts on the bicycle in a more controlled environment. This would provide information about the pressure distribution changes as riders accelerate and decelerate on the bicycle. Lastly, an Electrodiagnostic study should be performed with cyclists on a long ride in order to measure motor latencies while the subject is on the bike. This would provide the best measure for the relationship between the onset of handlebar palsy and riding condition causing the distress to the nerve.
References


Appendix A: Raw Data Analysis

A MATLAB script was written to analyze each dataset for this study. The first step in the analysis was to define the four portions of each trial. This was done using the accelerometer data, as seen below. The participants were asked to stop and place one foot on the ground between the different portions of the run. This is evident by the flattening out of the two signals from the accelerometer, as seen in Figure 44. These points were then used to divide up the data into the respective portions, flat, downhill, uphill, and flat again.
The figure below shows a plot of the raw force data for the left and right hands, for the downhill portion of a trial in the Drop Grip position for a particular Participant. There were fourteen analyzed participants for the road bike, with twelve trials per participant, with four portions to each trial (flat ground, downhill, uphill, and flat ground), the MATLAB script generated 672 of these plots. As seen in Figure 45, the accelerations, decelerations, and turns were trimmed from the data analysis. This is indicated by the vertical bands in Figure 45. The median values for each sensor are represented by the horizontal bands. These medians represent the force values with the cyclist at a steady

Figure 44: Sample Accelerometer Data
speed for the sensors for a given test condition. The same methods were used to analyze the mountain bike data.

The raw wrist posture data, as seen in Figure 46, was collected statically in the lab. When recording began, participants were to keep their wrist in a neutral posture, as seen by the first oval in the Figure 46. Participants then transitioned to the Top Grip on the Road
bike, marked by the second oval in Figure 46. The participants remained in this posture for roughly 10-15 seconds, before transitioning to the Hood Grip position. When transitioning, participants were asked to rotate the wrist rapidly to provide large spikes in the data, revealing transitions. The positive signal, zeroed at +2.5V, refers to the flexion/extension of the wrist and the negative signal, zeroed at -2.5V, refers to ulnar/radial deviation of the wrist. As mentioned in the Methods Section of the thesis, these signals were multiplexed. The ulnar/radial deviation signal was given the negative bias in order to distinguish the two signals in post-processing. The same method was used to analyze the wrist posture on the mountain bike.
The force sensors were calibrated using an Instron Machine from 0 to 66.7N with 13.34N increments. The raw data was used to create a linear calibration curve, specific to each sensor. The sensors were calibrated for data collection on the road and mountain bike, as well as before the design portion of the study. A sample calibration curve can be seen in Figure 47. A hysteresis effect was observed for each sensor, thus the loading and unloading paths were averaged to determine the calibration curve for each sensor. This
was also performed because riders may tend to increase and decrease the amount of force exerted on the handlebar as they ride.

Figure 47: Raw Force Data for Calibration of Sensor 10 – Instron Machine (0-66.7N with 13.34N increments)

Figure 48 shows the resulting calibration curve of the above raw data for Sensor 10.
Calibration checks were performed before and after participant testing to ensure accurate, repeatable measurements. This was performed by placing a 5 pound weight on each sensor before and after a participant test, and recording the output. The result of the calibration checks can be seen in Figure 49 for Sensor 7. Some of the fluctuations in the results were due to the inability to hold a five pound weight perfectly steady on the sensors. As seen in the figure, there is some fluctuation in the data, averaging between 0.1 to 0.2 volts. This usually corresponded to a ~4.5N to ~13N difference depending on the sensors.
Figure 49: Sensor Calibration Checks for Sensor 7 – Five lb. weight placed on each sensor before and after participant tests (each color band represents a before and after dataset for a particular participant)