

Analysis of Bicycle Pitch-Over in a Controlled Environment

2010-01-0064

Published
04/12/2010

Gerald P. Bretting, Henricus P. Jansen and Michael Callahan
Collision & Injury Dynamics Inc.

John Bogler and John Prunckle
ACT Lab LLC

Copyright © 2010 SAE International

ABSTRACT

In a controlled environment, bicycle crash tests were performed to analyze the dynamics of bicycle pitch-over, and the effect different test conditions would have on the motion of the bicyclist and the potential for serious head and neck injuries. The tests being evaluated within this paper will focus on a single size rider and bicycle with speed controlled between 19.3 and 22.5 kph (12.0 and 14.0 mph). The variables of the test conditions were the method of pitch-over initiation and configuration of the bicycle. Pitch-over was initiated by applying the front brake, impacting a rigid barrier, and inserting a dowel into the spokes of the front wheel. The bicycle configuration was varied by changing the frame, front fork, front wheel and stem. For all testing performed the event was captured on high speed video. As the testing progressed a force plate was added to measure the vertical loads and an impact plate was added to the barrier impacts to measure the horizontal impact loads. The data acquired from this series of tests provides insight into the dynamics of bicycle pitch-over, injury mechanisms, and the effect of bicycle component failure.

INTRODUCTION

Even though bicycle pitch-over accidents are a source of serious head and neck injuries, this type of accident has rarely been studied. Previously published work includes an SAE paper (Werner, 2001) evaluating All Terrain Bicycle pitch-over with both suspension and rigid forks and a Master's thesis (Andersen and Bergman, 1997-1998), written at Chalmers University of Technology, Gothenburg Sweden, evaluating the dynamics of pitch-over and the loads associated with the pitch-over event. The lack of analyses and

empirical data on the bicycle pitch-over event calls for more research in order to better understand both the bicycle and rider dynamics and kinematics.

Due to the high center of gravity (CG) of the bicycle and rider system and the short wheelbase of the bicycle, the bicyclist is particularly prone to pitch-over. During the pitch-over event, the bicyclist's head leads the way, increasing the probability of head impact and neck loading.

Common causes of bicycle pitch-over are over-application of the front brake, running into a fixed object, or an object becoming entrapped between the spokes of the front wheel and the fork blades. The Consumer Product Safety Commission's (CPSC) national study of Bicycle Use and Hazard Patterns (Allen, 1995) states that six (6) percent of all accidents are related to an object being caught in the spokes of a bicycle wheel. The CPSC report does not provide information regarding the percentages of front to rear wheel involvement and pitch-over can only occur when the object is caught in the front wheel.

Within this paper, we will discuss pitch-over dynamics, bicyclist motion, horizontal and vertical loading (where test data was acquired), and event timing for front brake over-application, insertion of a dowel into the front wheel, and frontal impact into a barrier. We will also discuss the effect that bicycle component failure has on pitch-over dynamics, bicyclist motion, horizontal and vertical loading and event timing.

DEFINING PITCH-OVER

Using the standard SAE vehicle coordinate system (SAE J670e), bicycle pitch-over is the rotation of the bicyclist and/

or bicycle about the pitch axis of the bicycle. The pitch-over event has been frequently called an “endo” or “endover”, which was so named because the back end of the bicycle was flying over the front end. The pitch-over event in which a rider is rotated and/or launched over the handlebars is due to abrupt deceleration of the bicycle. This creates the rotational moment about the front tire contact patch with the ground or the front axle. Pitch-over is initiated when the rear wheel of the bicycle leaves the ground and continues as bicyclist rotates over the handlebars, impacts the ground and tumbles/slides to rest. For the purposes of this paper, the end of the pitch-over event will be defined as when the head of the bicyclist impacts the protective pad.

Dividing the pitch-over event into five (5) segments will allow the terminology used throughout this paper to be defined and provide greater understanding of the event. The first segment is the abrupt deceleration of the bicycle. For a bicyclist in a normal seated position, a sustained deceleration rate greater than 0.7 g's will typically initiate the pitch-over event. The second segment is pitch-over initiation, which occurs when the rear wheel lifts off of the ground. The third segment is the initial trajectory, which is the motion of the bicyclist from the initiation of pitch-over until the bicyclist's center of gravity (CG) is directly above the front wheel contact patch. The fourth segment is when the front wheel lifts off of the ground. Front wheel lift off typically occurred before the bicyclist's CG reached the point where it was over the front tire contact patch. The fifth segment is the final trajectory which is the motion of the bicyclist from when the bicyclist's CG is directly above the front wheel contact patch until the bicyclist's head touches the protective pad.

DYNAMICS

Center of Gravity (CG) Location

For simplicity only the CG height (z axis) and the CG position about the longitudinal axis of the bicycle (x axis) are analyzed within this paper. Due to symmetry of the bicycle and rider about the x-z plane (mid plane), the lateral CG (y axis) location is assumed to be mid plane. The human body can be thought of as a system of body segments linked to each other at the major joints ([Winter, 1979](#) and [Van Cott, 1972](#)). This means that the mass distribution changes continuously as the body posture changes and the relative CG location depends on the body posture. The test bicyclist's CG was calculated with the bicyclist seated on the bicycle with the hands on the hoods of the brake levers and feet on the pedals. The position of the crank arms has minimal influence on CG location. The bicyclist's CG was calculated using anthropomorphic data for each body segment scaled to the specific height and weight of the bicyclist used in this study, [Figure 1](#).

The bicycle CG was determined by hanging the bicycle by a single point from two (2) different locations with a plumb bob at each hanging point. The CG was at the intersection of the lines defined by the two (2) plumb bob strings.

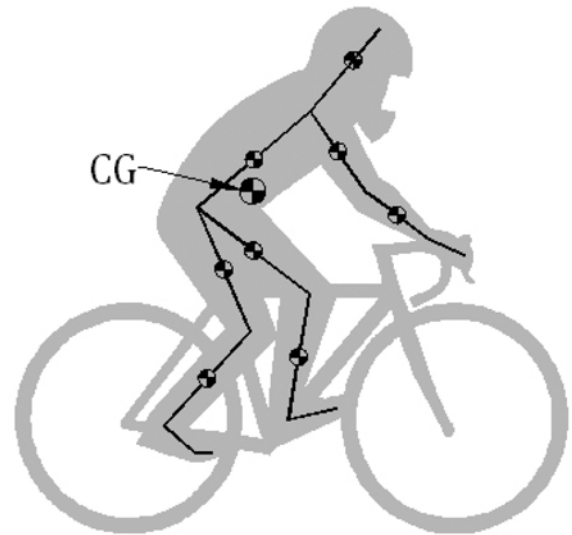


Figure 1. Center of Gravity for the bicyclist

Using a standard stem, the bicyclist's CG was located at 58.1 cm (22.9 inches) behind the front tire contact patch and 107.0 cm (42.1 inches) above the ground. The CG of the bicycle and rider system was located at 57.9 (22.8 inches) behind the front tire contact patch and 100.0 cm (39.4 inches) above the ground. As can be seen, the weight of the bicycle and its CG location has little overall effect on the CG of the bicycle and rider system. Using an adjustable stem, adjusted to achieve a maximum handlebar height, the bicyclist's CG was moved at 3.0 cm (1.2 inches) aft and 4.1 cm (1.6 inches) above the standard stem CG location.

The motion tracking software utilized did not have the capability to simultaneously track all of the body segments of the bicyclist. Therefore, the top of the iliac crest was selected as a close approximation of the bicyclist's CG and that location is used for all analysis associated with the trajectory of the bicyclist CG.

Minimum Deceleration Required for Pitch-Over

The minimum deceleration required to initiate pitch-over by stopping the rotation of the front wheel can be easily calculated by summing the moments of a decelerating bicycle about the front wheel contact patch (Point A) when the load on the rear wheel load (F_B) goes to zero (pitch-over initiation), [Figure 2](#).

This analysis reveals that most road bicyclists will pitch-over with deceleration rates between 0.6 and 0.7 g's. The deceleration rate is dependent on rider and bicycle size, the style of the bicycle and the rider's position on the bicycle.

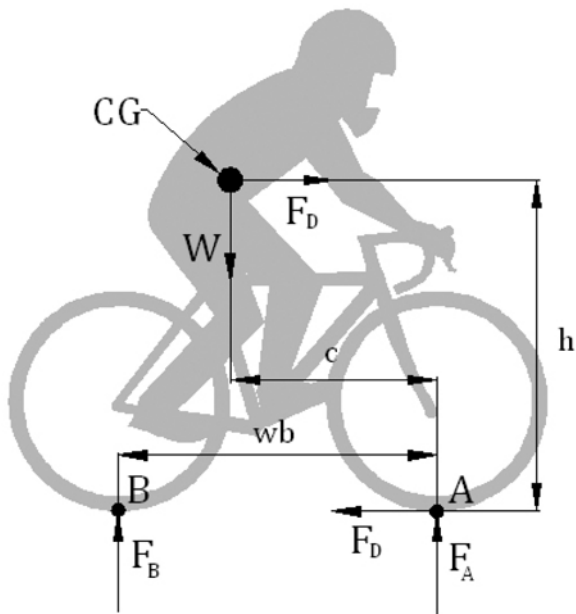


Figure 2. Free body diagram of forces during braking

$$\sum M_A = 0 = (F_B \times w_b) + (F_D \times h) - (W \times c)$$

Minimum velocity

During pitch-over, there is a deceleration of the bicycle, an angular acceleration of the bicycle and bicyclist, deflection of the bicycle frame and components, and the bicyclist's CG moves upwards. Some of the bicycle's initial kinetic energy is lost in the work performed in the deceleration of the bicycle and deflection of the bicycle frame and components. Furthermore, some of the initial kinetic energy must be converted into vertical and rotational velocity. Therefore, the bicycle and bicyclist system must have a minimum amount of kinetic energy (horizontal velocity) for pitch-over to occur.

The authors have previously performed a series of pitch-over tests associated with front brake application alone. One aspect of this testing was to determine the minimum velocity required for pitch-over for adult sized mountain and road bicycles. The minimum velocity required to complete pitch-over was determined by incrementally increasing the velocity until complete pitch-over was achieved. This testing revealed that a minimum velocity of approximately 12.1 kph [7.5 mph] was required to initiate and complete the pitch-over event. This minimum velocity is dependent on size of the bicycle and rider, the position of the rider on the bicycle, and the configuration of the bicycle. The results from this testing have not been previously published.

Instant center of rotation at pitch-over initiation

When initiating pitch-over, due to stopping the rotation of the front wheel, by either front brake application or insertion of an object into the spokes of the front wheel, the contact patch of the front tire with the ground surface is the instant center of rotation. The instant center of rotation changes for the rigid barrier impact from the front tire contact patch with the ground to the axle of the front hub. This is due to the fact that both the leading and lower edges of the front wheel are restrained from movement during rigid barrier impact versus only the front tire contact patch is restrained (friction only) during stoppage of the front wheel rotation. Furthermore, during the frontal impact the front wheel is free to rotate about the front axle versus the front wheel is not allowed to rotate about the axle when the wheel rotation is restrained by the front brake or dowel.

Front wheel lift off

Contrary to the traditional belief that the front wheel must be in contact with the ground for the bicycle to continue to pitch-over, the testing revealed that shortly after pitch-over initiation, the front wheel lifts off of the ground. At this time, the exact cause of this phenomenon has not been researched in detail but it is believed to be associated with two (2) factors. The first is a large vertical downward force that is generated at the front wheel contact patch at the initiation of pitch-over. This force vertically compresses the front tire, wheel, bicycle frame, and fork, and as the vertical downward force is relaxed, these components elastically rebound. The second factor is once the system CG has been accelerated upward and rotationally about the pitch axis (the creation of the large vertical downward force), it will continue to move upward until gravity can stop this motion. To further understand this phenomenon, testing would need to be performed to determine the combined spring rate of the frame, fork and front wheel and further review of the high speed video would be required to determine the correlation between front wheel lift off, the trajectory of the bicyclists CG and the vertical velocity of the bicyclist's CG.

TESTING

SETUP

The test setup consisted of a bicyclist, bicycle, sync flash, data acquisition system, wooden dowel shooter, high speed video camera, regular speed video cameras, still digital camera, and landing zone padding. During the initial tests (brake application tests and the first series of dowel insertion tests), no vertical loads were measured. To gain further understanding of the forces and reactions that were occurring as the bicycle pitched-over, vertical load plates were added to the remainder of the dowel insertion tests. During the barrier impact tests, both vertical and horizontal load plates were used.

Bicyclist

The bicyclist was a trained stuntman, who was a 70.5 kg (155 lb) male and 162.5 cm (64.0 inches) tall. To minimize injury, the bicyclist was equipped with the necessary safety equipment such as a full face helmet, body armor and a neck brace. The safety equipment added approximately 2.3 kgs (5.0 lbs) to the weight of the bicyclist. Targets were placed on the right side of the bicyclist's helmet, top of the iliac crest, shoulder, the joints of the arms and legs, and several locations on the right side of the bicycle. The targets were later used in the analysis of the high speed video.

Landing zone

A landing zone for the bicyclist was created using 15 cm (6 inches) thick padding to minimize injury upon impact with the ground. These pads were placed in the area where the bicyclist was expected to land and roll out, based on the planned pitch-over initiation point and speed.

Load plates

The vertical load plates were designed to measure the normal forces on the bicycle wheels as the bicycle was in the process of pitching-over. During the dowel insertion testing, the exact location of pitch-over initiation varied by as much as one (1) meter (39 inches). Due to this variation in the pitch-over initiation location and the wheelbase of the bicycle, two (2) identical vertical load plates were placed end to end to create a 2.44 m (8 feet) long surface for measurement of the vertical load. Each vertical load plate consisted of two (2) aluminum plates sandwiching four (4) 455 kg (1000 lb) load cells mounted at the corners. The dimensions of the top plate were 61 cm wide by 122 cm long by 1.3 cm high (24 by 48 × 0.5 inches), [Figure 3](#). Grip tape was applied to the surface of the top plate to prevent the front wheel from sliding, when the rotation of the front wheel was stopped. The grip tape simulated a new rough concrete surface that had a coefficient of friction with the bicycle tire of approximately 1.0. Following initial testing the vertical load plates were redesigned to be made of steel and resized to 45.7 × 91.4 × 1.8 cm (18.0 × 36.0 × 0.7 inches) to minimize the deflection of the top plate. The two (2) vertical load plates were placed end to end to create a 1.8 (6 feet) long surface for measurement of the vertical load.



Figure 3. Vertical load plate

The impact load plate was an aluminum plate, 15.2 × 15.2 × 2.5 cm (6.0 × 6.0 × 1.0 inches) that was mounted to a rigid wall by three (3) linear bearings, oriented in the loading axis. Three (3) 455 kg (1000 lb) pancake load cells were mounted between the rigid wall and the load plate, [Figure 4](#). The center of the load plate was located approximately 32.5 cm (12.8 inches) above the top of the vertical load plate, which is the height of the centerline of the hub on a 700 C bicycle wheel. This height was selected to locate the impact load in the center of the three (3) load cells to minimize any eccentric loading.

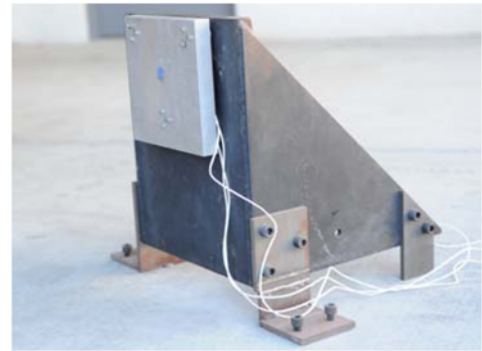


Figure 4. Impact load plate

SYNC FLASH

A manually operated camera flash was used to allow synchronization of the load plate data to the high speed video. The sync flash was triggered when the front wheel of the bicycle entered the first vertical load plate. The sync flash was only used when load plate data was being acquired.

DATA ACQUISITION

The load plate and sync flash data were acquired using a National Instruments Data Acquisition Board and LabView 7.0. The data was acquired at a rate of 1,000 Hz.

DOWEL SHOOTER

A wooden dowel shooter was designed to insert a dowel into the front spokes of a bicycle wheel and initiate a pitch-over event by stopping the rotation of the wheel. The shooter was a spring loaded tube mounted to the right fork blade and was triggered by the bicyclist, through a cable attached to the rear brake lever, [Figure 5](#). The shooter shot a 2.5 cm (1.0 inches) diameter wooden dowel 28 cm (11 inches) long, at approximately 6.4 mps (21.0 fps) into the spokes of the front wheel behind the fork blades. The bicyclist was instructed to trigger the shooter when he was approximately 1.5 m (5 feet) from the leading edge of the pad.



Figure 5. Dowel shooter

VIDEO AND STILL CAMERA DOCUMENTATION

A Phantom 5.1 high speed video camera was positioned perpendicular to the path of travel of the bicyclist, such that the center of the frame was in the intended area of pitch-over at the height of the bicyclist's CG when he was on the bicycle. The high speed camera remained stationary for all tests completed within a day, so that the video could be scaled and analyzed. During the brake application tests and the initial dowel insertion tests, the high speed camera was setup to capture at 1200 frames per second, but captured these tests at 600 frames per second. The remaining dowel insertion and barrier impact tests were captured at 1200 frames per second.

Regular speed video was also used to capture the tests in real time from three (3) different angles. All three of these cameras were Panasonic Pro HD-1 cameras, capturing in High Definition mode (720p) at 29.97 (30) frames per second. One of these video cameras was positioned next to the high speed camera. The next video camera was placed at approximately 45° to the travel path of the bicycle and the last video camera was placed in line with the travel path of the bicycle. Similarly, all of these video cameras were positioned so that the center of the frame was at the intended pitch-over area (the camera perpendicular to the path of the bicycle was positioned at the height of the bicyclist's CG) and they remained stationary throughout the testing day.

A Nikon D2X was also used to capture the tests with still imagery. This camera was also placed next to the high speed camera and was positioned so that the center of the frame was at the intended pitch-over area and at the height of the bicyclist's CG. This camera captured the initial tests at 5.5 frames per second and the later tests at 8 frames per second.

TEST ARTICLES

The intent of this test program was to test a single sized bicycle and rider in three (3) differently initiated pitch-over events. These pitch-over events were initiated by front brake application, dowel insertion into the front wheel, and barrier impact. The test bicycles were all 52.0 cm (20.5 inches) frames similarly equipped with the exception of the front forks, front wheels, and stems. [Figures 6](#) and [7](#) describe the major components of the bicycle and fork, respectively.

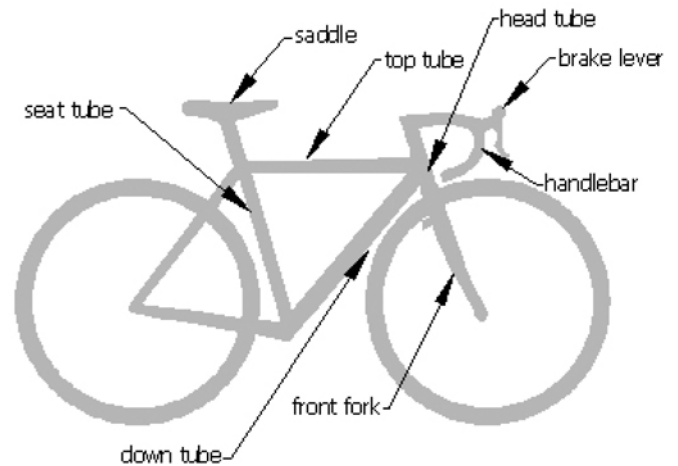


Figure 6. Major frame and bicycle components

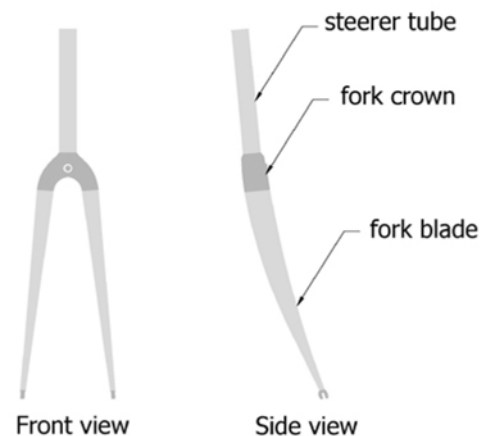


Figure 7. Front fork

All of the bicycles were equipped with platform pedals, so that there was no attachment between the bicyclist's feet and the pedals. Three carbon composite bicycle frames were used in all of the braking and dowel insertion tests. During the barrier impact test, these frames failed and the final six (6) barrier impact tests were performed with an aluminum frame of the same size.

A secondary intent of the test program was to vary the material the fork was made of and the diameter of the steerer tube to study how the pitch-over event was affected by the