35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Development of a Point-of-Care Medical Device to Measure Head Impact in Contact Sports

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***Abstract*— This paper presents a prototype of a wireless, point-of-care medical device to measure head impacts in contact or collision sports. The device is currently capable of measuring linear acceleration, time, and the duration of impact. The location of the impact can also be recorded by scaling the prototype design to multiple devices. An experimental apparatus was built to simulate head impacts and to verify the data from the device. Preliminary results show that the biomechanical measures from the device are sufficiently accurate.**

I. INTRODUCTION

A concussion is often defined as an alteration in mental status as a consequence of trauma to the head that may or may not involve loss of consciousness [1]. It occurs very frequently in collision or contact sports including, but not limited to football, soccer, ice hockey and boxing. Every year, a large number of high school students in the United States are diagnosed with concussions [2]. This can be partially attributed to the brain tissues of teenagers not being fully developed which makes them more susceptible to head injuries than adults [3]. Several studies have also shown that repetitive head injuries can result in long term effects such as reduction of brain injury threshold, depression, chronic traumatic encephalopathy and slowed recovery of neurological function [4-6]. Furthermore, repeated concussions within short intervals of time can be fatal [1]. Besides impact duration, other biomechanical measures including linear acceleration, rotational acceleration, and impact location are associated with determination of concussion risks [7]. Hence, a long-term objective of this research is to provide reliable biomechanical information to assist with point-of-care diagnosis of concussions in athletes.

Several head impact detection devices have been developed to assess various biomechanical measures [8-11]. Some of these devices are limited to use in helmet-based sports only. Other limitations include high cost, requirement of custom software to receive and analyze data, and in some cases, the device is part of a mouth guard that makes it difficult to use. The goal of this paper is to present a prototype design of a low-cost, point-of-care device called, CONLISUS (meaning: 'collision' or 'clash' in Latin), to measure linear acceleration and duration of head impacts in contact sports. The device is extremely easy-to-use and portable. The measured acceleration data is wirelessly transmitted to a laptop computer for monitoring and data analysis purposes.

II. SYSTEM DESIGN

There are three major components in the CONLISUS device: (1) Microcontroller, (2) Accelerometer, (3) ZigBee module. A block diagram of the device is shown in Fig. 1.

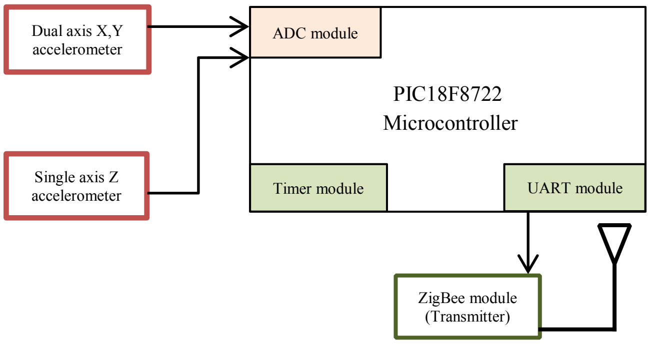

Figure 1. Block diagram of CONSLISUS device

A. *PIC Microcontroller*

A PIC18F8722 microcontroller (Microchip Technology Inc.) is the core of the device that controls other hardware components. It is an 8-bit microcontroller with 4 Kbytes of data memory, 10-bit Analog to Digital Converter (ADC) with 15 channels, 2 Enhanced Universal Synchronous Asynchronous Receiver Transmitter (USART) modules and 4 timers that can be operated in 8-bit or 16-bit mode.

B. *Accelerometer*

There are two orthogonal high-g accelerometers (Freescale^{TM} Semiconductor, Inc.): (1) Dual axis (X and Y) accelerometer, (2) Z axis accelerometer. Both the sensors are surface mount micromachined accelerometers. The range for X, Y and Z axes are ±100g, ±30g and ±150g, respectively (where $g = 9.8\ m/s^2$ is the acceleration due to gravity).

The threshold value of acceleration is set to 5g. All values beyond 5g are recorded and stored into the data memory of

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the microcontroller. A timer is run simultaneously to provide a time-stamp for each acceleration value that is being recorded. Each axis has a dedicated buffer allocated within the data memory to store both, the acceleration value and the corresponding time stamp.

C. *ZigBee Module*

The data memory on the PIC microcontroller is limited to 4 KB and hence, it is not possible to store values over large durations of time. As an alternative, a ZigBee module is used to transmit data from the microcontroller to a laptop receiver. The Xbee® ZigBee module from Digi International Inc., is used for this purpose. Each Xbee kit can be configured as a router or a transmitter. The device has an Xbee transmitter configured as a ZigBee transmitter/router with the destination address set to that of the laptop receiver. The receiver at the laptop is set as a coordinator with the source address set to that of the device transmitter. This is a point-to-point ZigBee network with one transmitter and one coordinator. In case of multiple devices, a multi-point network can be formed with the laptop receiver acting as the coordinator and all other devices can act as transmitters/routers.

The device measures linear acceleration as a result of any vibration, impact or collision using the two accelerometer chips. The output of each accelerometer is an analog voltage signal proportional to the measured acceleration. This voltage is converted to a 10-bit digital value by the ADC module and is stored in the data memory of the microcontroller along with a timestamp. This value is then sent to a base station (laptop receiver) using the ZigBee module. The device is wireless, battery-operated and does not require any external software to collect data. The size of the entire device (shown in Fig. 2) is 2 x 2 inches and weighs 21.21 grams (0.748 oz). These features make the device extremely portable and well-suited for point-of-care testing. A summary of various device specifications is shown in Table I.

Figure 2. CONLISUS device (1a – Single axis Z accelerometer, 1b – Dual axis X, Y accelerometer, 2 – Microcontroller, 3 – ZigBee Transmitter)

TABLE I. DEVICE SPECIFICATIONS

Dimension (W x L)	2 x 2 inches
Weight	21.21 grams
Battery Life[a]	~ 50 hours
Communication Range	Up to 130 ft.
Baud Rate	125,000 bps
Prototype Cost	~ $70

[a] Using a 9V AA alkaline cell

III. RESULTS AND VALIDATION

An experimental set-up was built to generate impacts/collisions and verify the data obtained from the CONLISUS device. Fig. 3 shows the design and various components involved in the test set-up. The experimental method is as follows: A derby car is pulled against a bungee cord and then released to collide with a compression spring attached at the end of the track. Steel screws (not shown in Fig. 3) are fastened to the colliding face of the car and the spring. The heads of the screws face each other so as to create an impact during collision. This collision is used to mimic a head impact or any kind of blow to the head.

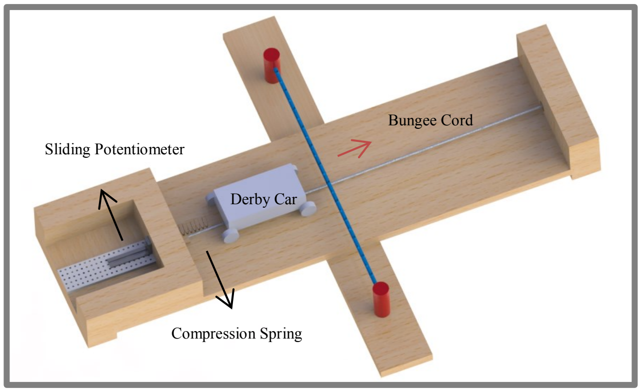

Figure 3. Experimental set-up to simulate head impact

A. *Functional Testing*

The experiment was performed with the CONLISUS device mounted and fixed on top of the derby car. The graph in Fig. 4 shows the measured acceleration throughout the experiment. It also clearly shows the drastic change in acceleration at the time of collision. Fig. 5 shows an expanded version that is focused around the peak acceleration in Fig. 4. This graph can be used to observe exact acceleration changes before, during and after the impact/collision. It can also be used to measure the duration of the impact.

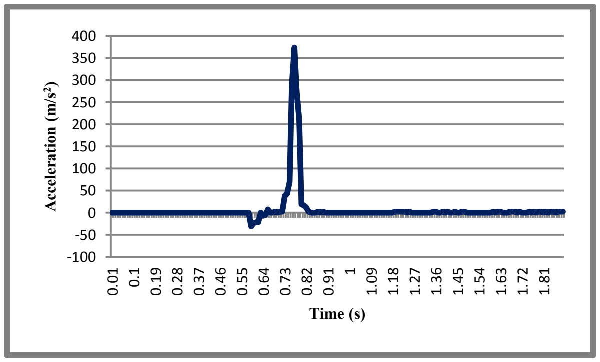

Figure 4. Acceleration values vs Time plot as measured from CONLISUS for stretching distance of 15 cm

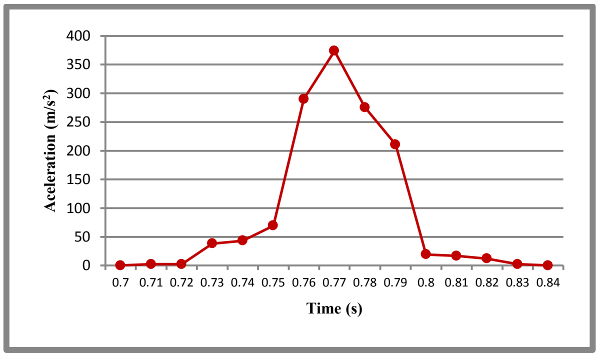

Figure 5. Peak Acceleration (expanded from Fig. 4) during collision

B. *Validation*

In order to validate the data from the device, the acceleration values were computed using a method based on collision theory. In this method, an inelastic collision between the derby car and spring is used to generate impacts/collisions. Since the momentum is conserved in inelastic collisions, this principle can be used to determine acceleration values and thus, validate the system.

All measurements and computation were done using a PIC24 microcontroller demonstration board (Microchip Technology Inc.). A brief description of the method is as follows:

- A compression spring of known spring constant (k=11.751 KN/m) is placed at the end of the track.
- A Panasonic sliding potentiometer (see Fig. 3) is used to measure compression length of spring, X, when hit by the car. The total force applied to the spring is measured using Hooke's Law ($F = kX$).
- Using this force, the acceleration is then simply measured using, $F = ma$, where m is the mass of the car assembly that includes the mass of the CONSLISUS device, battery and a custom plastic mount to hold the device (155 grams).

When the derby car is collided against the spring, the acceleration values and a time stamp from the CONLISUS device are transmitted to the laptop receiver. The peak acceleration value is also measured and computed by the microcontroller of the experimental set-up. The graph shown in Fig. 6 plots the peak acceleration values from both the CONLISUS device and the experimental set-up for different stretching distances. Both the values are comparable with an average relative error of 4.08%. Since the force applied to the car is proportional to the stretching distance of the bungee cord, the peak acceleration should increase with the increase in stretching distance of the cord. This effect can be directly observed from Fig. 6.

A study that recorded head accelerations on college football players observed that the average peak linear acceleration was around 13g, 10g, and 8g along the x, y, and z axis, respectively, and the average peak resultant linear acceleration was around 23g [8]. While there are no studies to the authors' knowledge that confirm threshold acceleration values for concussion, the CONLISUS device is set-up to measure linear accelerations up to 100g.

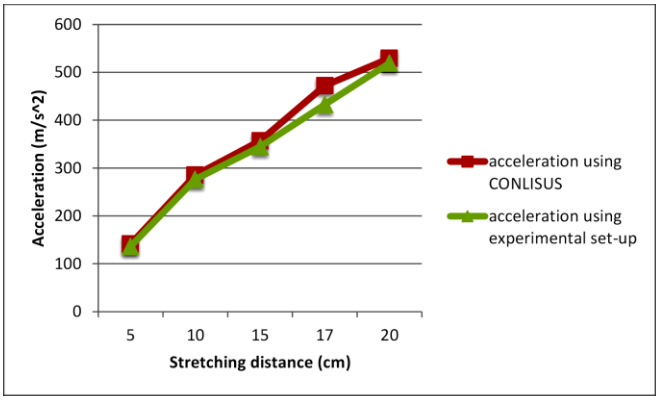

Figure 6. Comparison of peak acceleration values from CONLISUS and the experiment set-up for different stretching distances

IV. DISCUSSION

In summary, a low-cost wireless device has been prototyped to reliably measure acceleration of head impacts along with the time and duration of the impact. As the communication is based on ZigBee protocol, multiple CONLISUS devices can be easily configured to measure impacts of players at different locations on the field of play. Furthermore, it is more like a *plug-and-play* device that can be attached to any place that is susceptible to impacts. Unlike many commercial devices, CONLISUS does not require any proprietary software. It is platform independent and needs only a receiver terminal that is readily available for all the operating systems. Since most of the data is instantaneously transmitted to a receiver on a laptop, a large amount of impact data can be stored over a period of time. This data can be used to generate a detailed report of impacts endured by an athlete during a game. The collection of real-time data can also help in the study of long-term effects of repeated sports-related brain injury.

Certainly, several enhancements are needed for the system to efficiently support clinical diagnosis of concussions. As a part of this effort, the following are some immediate steps:

- Plan and execute a pilot study on football players during practice sessions: This can be done by placing a CONLISUS device in the helmet of each player. The communication module can then be configured to work as a point-to-multipoint network. In this way, a central receiver can gather impact data from the device in every player's helmet.
- Redesign the sensor system to measure both linear and rotational acceleration of impacts.
- Develop an application that can be used to collect and analyze data on a tablet computer rather than a laptop.

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