A Standard Impact Test Procedure for Football/Hockey Shoulder Pads

by

Alvan Eric P. Loreto

Submitted to the Department of Mechanical
Engineering in Partial Fulfillment of the
Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

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June 2001

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A Standard Impact Test Procedure
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Submitted to the Department of Mechanical Engineering
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ABSTRACT

Impact testing was performed on a prototype shoulder pad specimen (Specimen B) for use in the sports of both hockey and football. The impact was delivered by a free-rolling steel rod housed in linear bearings with a hockey puck attached to its end, which is imparted kinetic energy for impact by a spring-loaded striking apparatus. Data was collected from this specimen and compared to data of similar trials performed on market-standard shoulder pad specimens A (football only) and C (hockey only). The results indicate that Specimen B offers impact force protection comparable to market-standard levels.

The particular impact testing procedure used in this project was then analyzed, with the chief purpose of examining its possible development into an industry-wide standardized testing method for hockey/football protective padding for the upper body.

Thesis Supervisor: Kim B. Blair, PhD
Title: Director, MIT Center for Sports Innovation

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INTRODUCTION

For a significant amount of the world population, participation in athletics is a pervasive form of recreation from the stressful moments of life. A smaller percentage of people, highly skilled and often admired by others, view athletics as a means of financial support for themselves and their loved ones. Yet regardless of what the individual makes as his or her motivation and agenda during participation, a major priority while engaging in athletics is the prevention of personal physical injury.

For athletes on the youthful end of the participation spectrum, high-impact team sports are an attractive option for reaping the benefits, ideals, and excitement athletic competition is capable of offering. Two of these sports in particular, hockey and American football, continue to grow in popularity around the world, despite comparatively high incidence of physical injury that oftentimes is quite severe in nature. Therefore, the ability of protective equipment to uphold at all times a high standard of integrity is always in demand from all who associate themselves with these two sports.

In football and hockey, the rules allow players to careen forcefully into their opponents in order to prevent them from scoring. Using primarily their opponent's body as their brake, these athletes decelerate to zero in a span of less than half a second after zooming along at top speeds of 11 m/s (running) and 15 m/s (skating). A player often enjoys an adrenaline rush and a sense of machismo from the resulting kinetic energy transfer to their opponent, on account of the embarrassment and physical pain subsequently associated with that opponent's abrupt and forceful obedience to Newton's Second Law ("For every action there is an equal but opposite reaction."). Collisions at such velocities may prove damaging to the vital organs of either the hitter or the receiver of the hit, should one or both not be wearing adequate protective equipment. (Certainly, there are occurrences of injury even when players are adequately and properly protected; however, protective padding is lowers the risk of injury by absorbing some of the impact energy directed to the body.)

Because of the form and nature of most hits in the hockey rink and on the football field gridiron, the body parts exposed to the brunt of the impact forces are the head and the shoulder area. Without protection, impacts to the head are generally life-threatening, whereas impacts to the shoulder area generally are not. This observation reasonably explains why testing for head protection for the sports of hockey and football conforms to a standardized process[1] to ensure each piece of equipment minimizes to the fullest the risk of injury, but no equivalent standardized testing method exists for shoulder area padding. Nevertheless, the occurrence of shoulder area injuries in these sports is painful and damaging enough to the athlete to keep him or her out of competition for extended periods of time. Any athlete would desire to maximize the protection in this area, while of course minimizing restriction on range of motion.

Organizations such as ASTM (American Society of Testing Methods), NOCSAE (National Operating Committee on Standards for Athletic Equipment), and CSA (Canadian Standards Association) have published documents explicitly outlining the standardized testing method for football and hockey helmets. In terms of shoulder pads, the existing document of closest relevance is ASTM's F355-95, entitled "Standard Test Method for Shock-Absorbing Properties of Playing Surface Systems and Materials." This document includes the following clause in it: "This test method may also be used to measure the shock-attenuation properties of materials used as protective padding, such as the padding on… football goal posts, gymnasium wall, shoulder pads, body padding, etc. It should not be used, without some modifications, to test the finished products." This clause captures the essence of what this thesis project aims to accomplish.

The main goals of this thesis project are:

1) to apply the general statements of ASTM F355-95 to a specific test apparatus and procedure;
2) to use this apparatus and test procedure to compare a prototype football/hockey shoulder padding to existing football and hockey shoulder pad samples; and
3) to research and provide insight on the process of adapting ASTM F355-95 into an independent standard test method specifically for shoulder/body padding.

Because of its explicit recommendation in its wording, ASTM F355-95 serves as an appropriate starting point of reference for integrity testing of shoulder pads. Conforming as closely as possible to the terms and conditions of this existing document is valuable to future development outside this project. Thus, it is important that the general provisions of ASTM F355-95 regarding apparatus, procedure, and analysis apply while carrying out this thesis research.

It is this researcher's hope that the findings of this project will be reviewed by organizations such as the ASTM, and in doing so they will incorporate some of its elements in their future development of standards regarding protective equipment for athletics.

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[1] Ref. ASTM F429-97, ASTM F717-89, ASTM F513-95, ASTM F1587-96.

APPARATUS

The apparatus for performing the impact testing on the shoulder/body padding consists of three components: the impact device, the specimen holding assembly, and the data acquisition system. The general nature of the provisions set forth in Section 6 of ASTM F355-95 allows appreciable flexibility in choosing the specifics of each of the three components. For this particular apparatus, the impact device and specimen holder have been chosen on the basis of their availability. However, the method of data collection has been more carefully scrutinized with the intent of providing simpler and more specific instructions for future impact testing procedures.

Impact Device

ASTM F355-95 makes no stipulations on the impact device, other than it deliver an impact using a missile of known mass and geometry. This certainly applies to the machine used in this thesis project, a relatively simple spring-loaded horizontal impact delivery system known as FRED. A photo of FRED, which stands for Free-Rolling Energy Device, is shown in Figure 1.

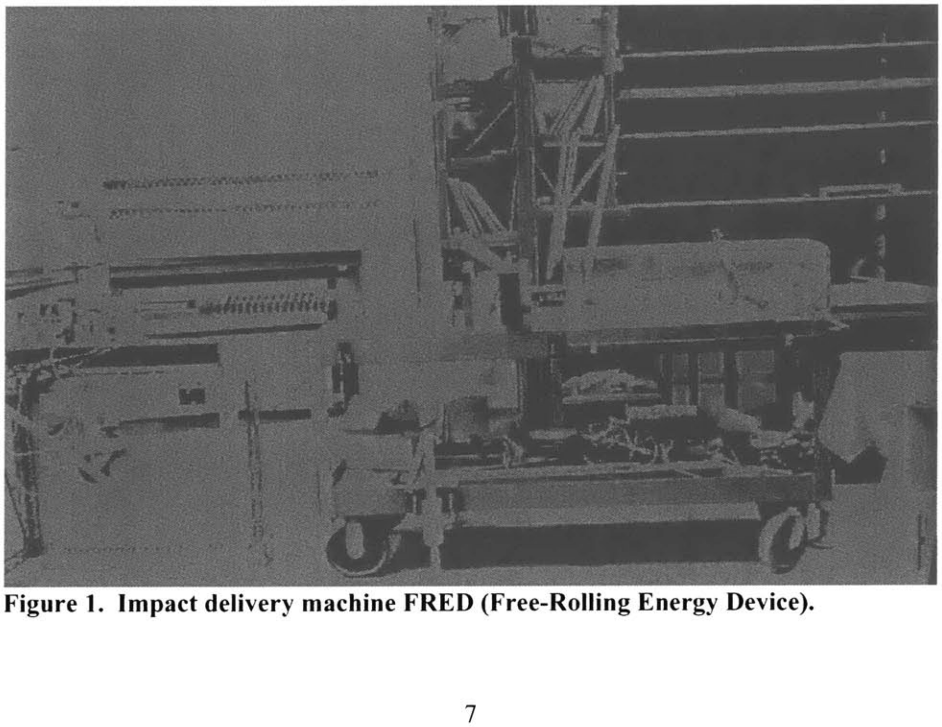


Figure 1. Impact delivery machine FRED (Free-Rolling Energy Device).

FRED was designed in 1987 by Darron Tebon and Sen Hao Lai under the supervision of MIT professor James Mar. Its original purpose was for the study of impact tolerance of composite sandwich panels. The driving factors in the design were to create an impact device that could provide a low-velocity, variable-mass impact with no repeated strikes due to impactor bouncing. The final result was an easy-to-operate yet durable apparatus that adequately meets those goals, with the added feature of striking specimens placed in an upright (vertical) rather than prone (horizontal) orientation.

A diagram of FRED is shown in Figure 2. FRED's appreciable simplicity explains why it functions well with no maintenance and has had no major repairs in its 14-year history even after operation hiatuses of 4 and 6 years. The diagram specifies the two main subassemblies of FRED, which are the striker unit and the impactor unit.

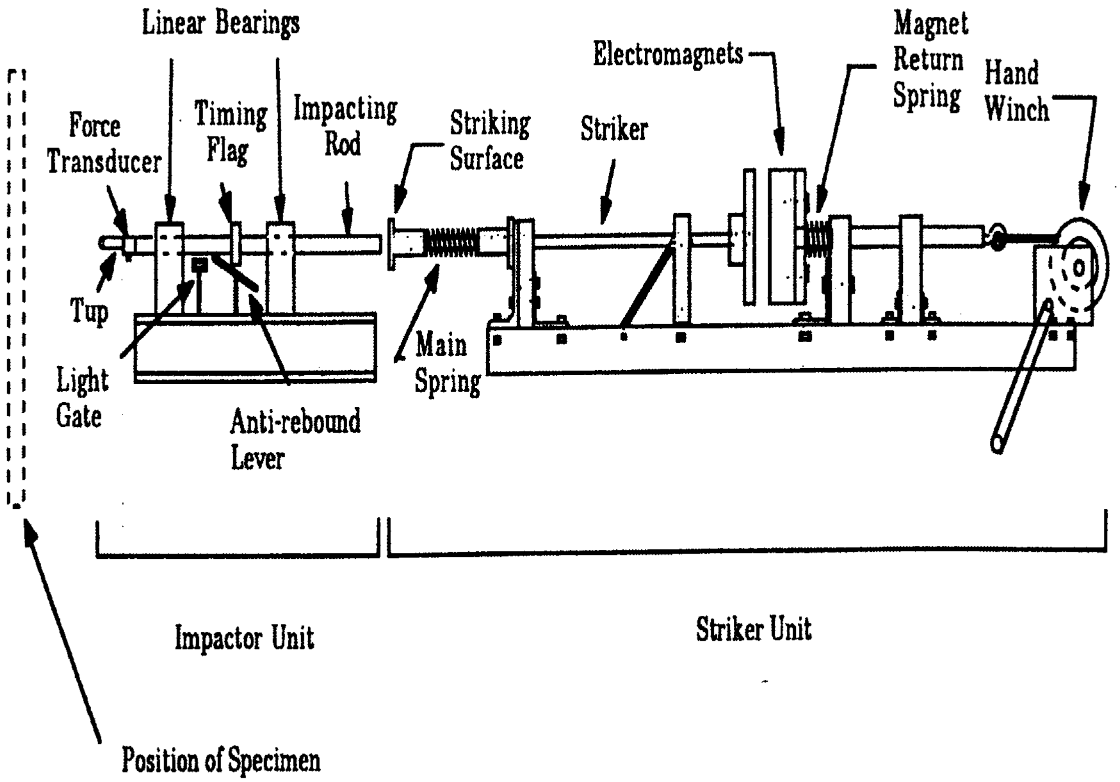


Figure 2. Subassembly diagram of FRED.

Figure 3 illustrates the striker unit, which consists of two long rod assemblies engaged end-to-end through the powering of two 8" x 4" x 3" electromagnets. The front rod assembly has a circular striking surface on one extreme, the square iron face to engage the electromagnets at the other, and the heavy-duty energy storage spring in between. The rear rod assembly has the electromagnets connected to a hand winch, with a spring in between to return the electromagnets to the iron face after disengagement.

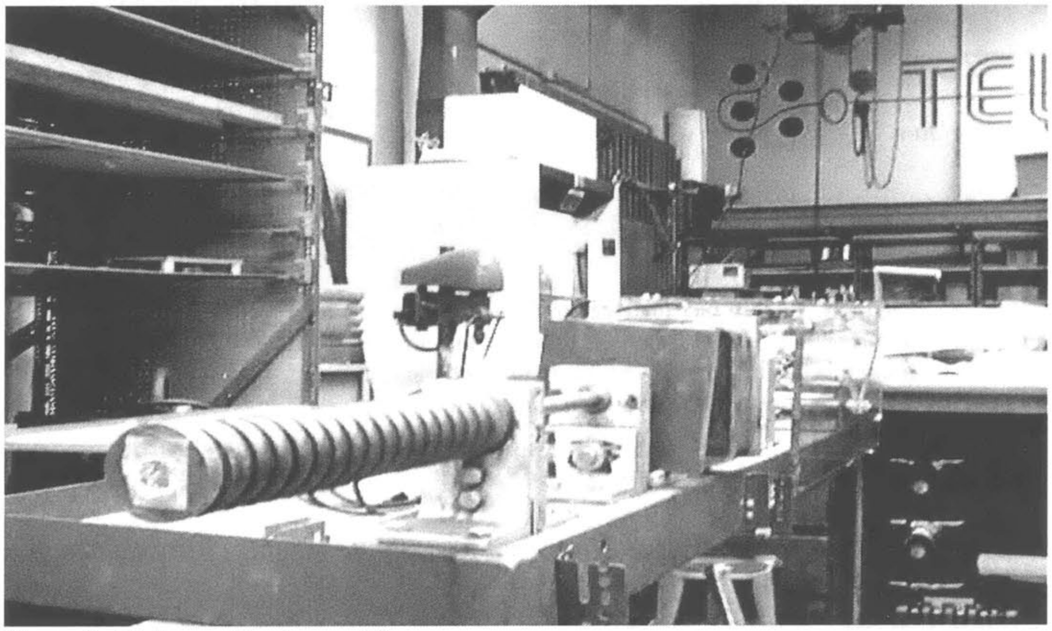


Figure 3. Striker unit subassembly.

To operate the striker unit, the magnets are first powered via their switch box (Figure 4), which runs off a standard AC wall outlet. Doing so locks the iron face of the front rod onto the electromagnets, creating a unified rod assembly. The assembly is then drawn back by cranking the hand winch clockwise. This in turn compresses the spring behind the striking surface, storing energy in the unit. Flipping the electromagnetic power switch to off releases the front rod assembly, sending the striking surface forward at a maximum velocity linearly proportional to the distance the spring was compressed. On FRED, this distance is measured by tracking the movement of one edge of the square

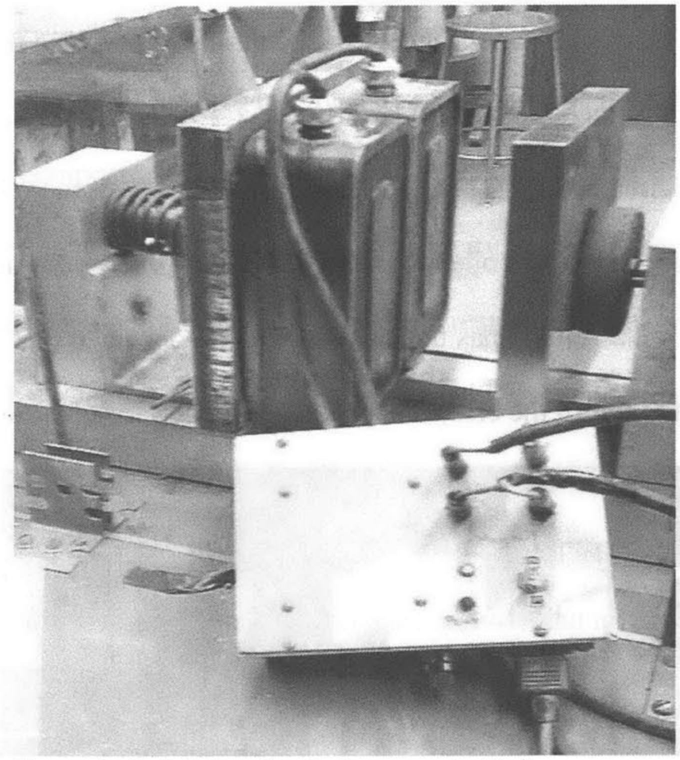


Figure 4. Switch box for electromagnets. Unit possesses on/off switch, power indicators for box and magnets, fuse holder, AC outlet, and connectors to electromagnets. Electromagnets are shown in background.

iron face with a ruler affixed to the assembly base. After firing, the winch is cranked counterclockwise, allowing the magnet return spring to push the magnets forward to the iron face for re-engagement.

The impactor unit, which transfers the energy cleanly from the striker unit to the specimen, is illustrated in Figures 5 and 6. A 3/8" diameter impacting rod of solid steel slides back and forth on two linear bearings set in upright housings. The end of the impacting rod that contacts the striking unit is a simple flat face, but at the other end, the end that interacts with the specimen, the rod possesses more noteworthy characteristics. A threaded hole along the central axis of the rod allows a force transducer to be attached to its end, and attached to that transducer is a hemispherical aluminum impacting surface known as a tup. Tups are interchangeable to alter the mass, size, and shape impacting

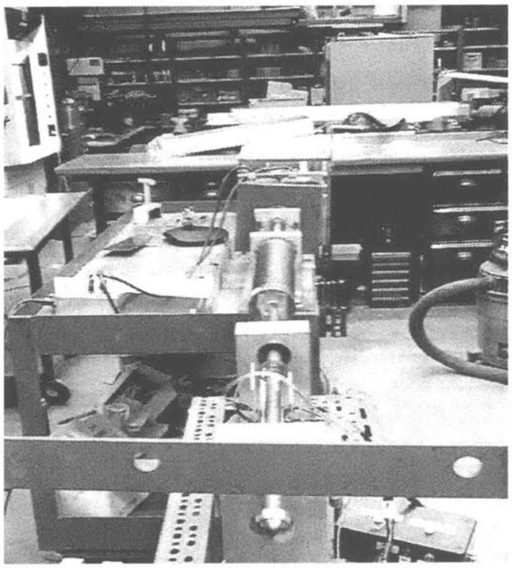


Figure 5. Impactor unit (foreground, with circular tip). Large crossbar across bottom is part of specimen holding assembly. Striker unit can be seen in background.

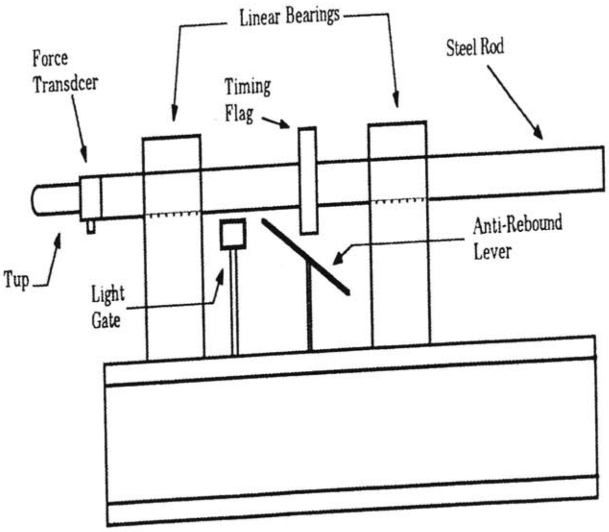


Figure 6. Diagram of impactor unit.

the specimen, in accordance with Section 4.2.2 of ASTM F355-95. Figure 7 shows the different tups manufactured for FRED throughout its history; for this thesis project a new tup was fittingly fashioned out of a regulation hockey puck (galvanized rubber, flat circular face, 1.4" diameter).

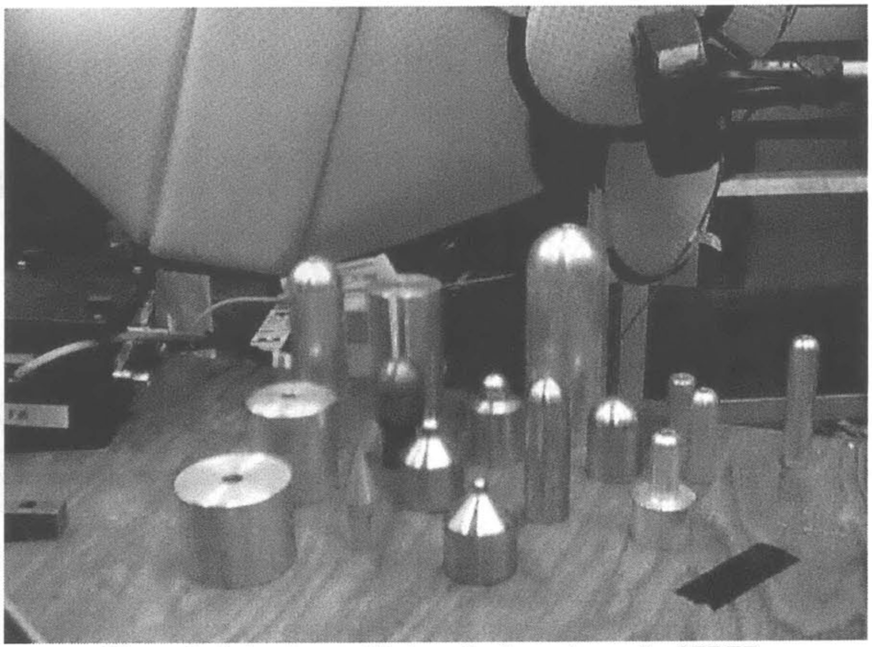


Figure 7. Interchangeable tups for impactor unit of FRED.

On the impacting rod in between the bearing housings is a rubber black donut, which serves a twofold purpose. First, the donut is a timing flag that triggers the light sensors, allowing the velocity of the impacting rod to be recorded. Second, the donut activates the anti-rebound lever of the impactor unit. This lever is a spring-loaded seesaw that catches against the donut should the impacting rod move toward the specimen again after the initial contact.

In operation, the impacting rod receives energy from the face of the striker unit and slides forward. The anti-rebound lever, which is initially oriented with the higher end on the specimen side, is triggered by the donut as it moves, which switches the lever's orientation. The tup strikes the specimen, and the rod bounces back toward the striker unit. As mentioned, the triggering of the lever prevents the impacting rod from contacting the specimen more than once. After impact occurs, the rod is slid back into its original position, and the anti-rebound lever is reset to its initial orientation for another trial.

Specimen Holding Assembly

Essentially, the specimen holding assembly (Figures 9 and 10) is a bulky drill press stand that easily meets the anvil mass stipulation of ASTM F355-95 Section 6.1. A height-adjustable mounting plate is clamped to an upright post. Eight large bolts fasten securely onto the mounting plate a two-arm extension that suspends the specimen in a vertical orientation (Figure 11). In this extension, a cumbersome unit weighing around 70 lb, sits the jig which holds the specimen.

The jig secures the specimen by clamping it between four sets of aluminum bars, as shown in Figure 12. Eight threaded rods are bolted into the baseplate of the jig, and

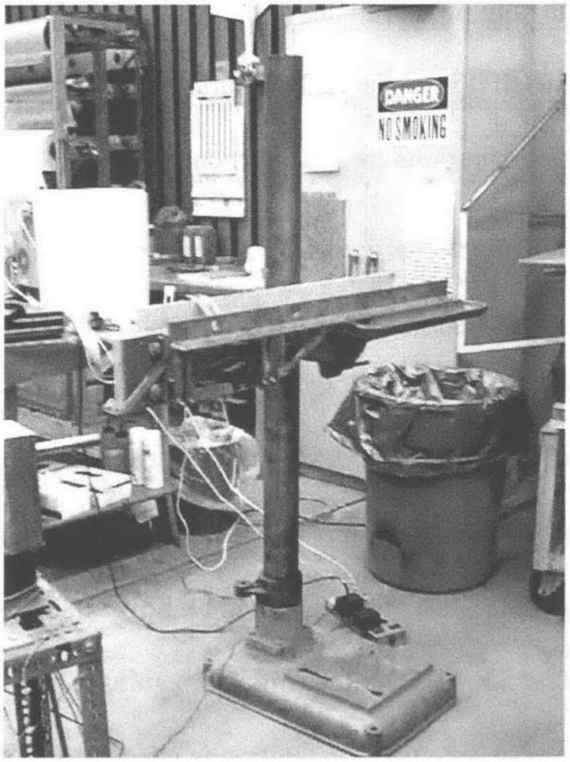


Figure 8. Specimen holding assembly.

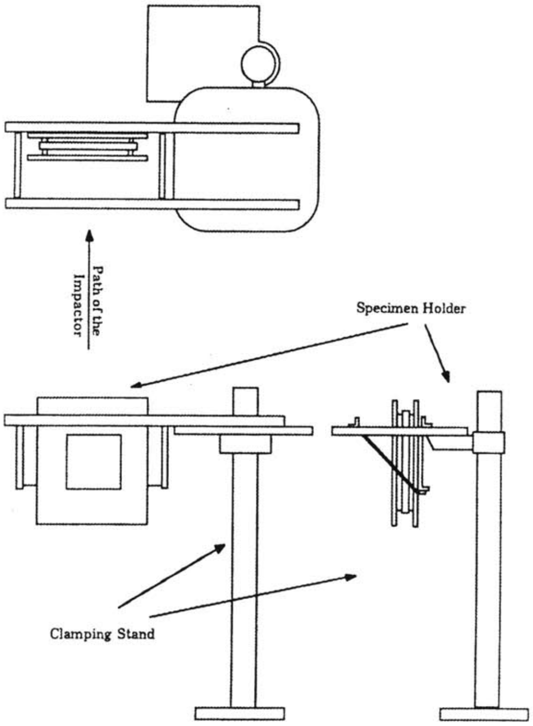


Figure 9. Top-, side-, and front-view diagram of specimen holding assembly.

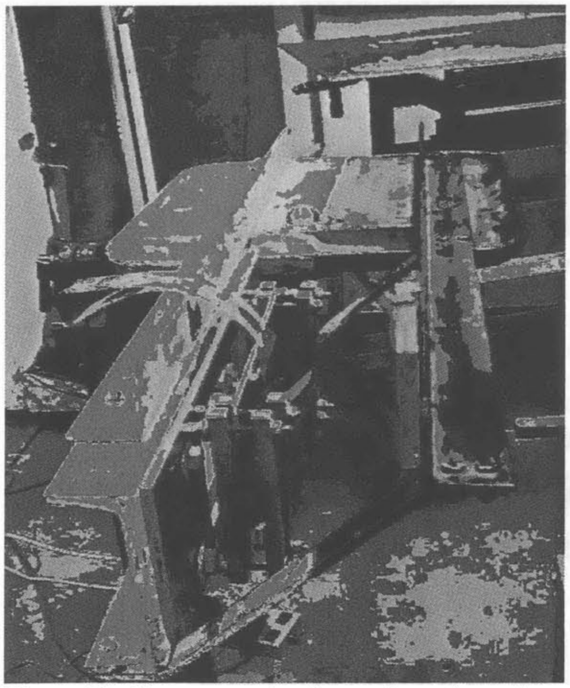


Figure 10. Two-arm extension and specimen jig.

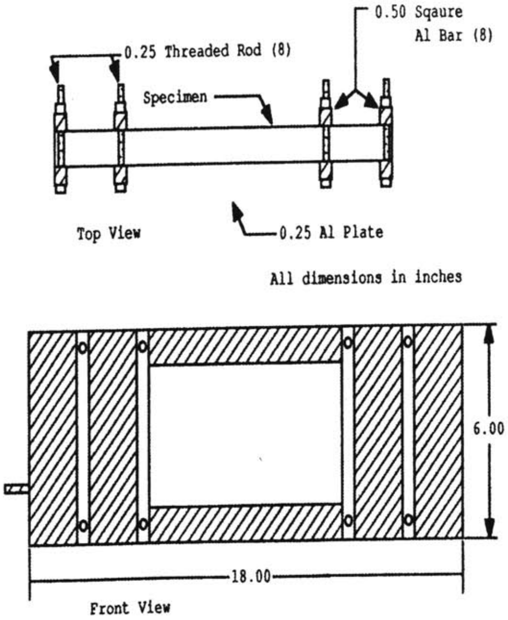


Figure 11. Diagram of specimen jig.

one bar from each set is placed through the rods onto the baseplate. The specimen is placed into the jig, and the other four bars sandwich it into place. Bolts are then placed on top to immobilize the specimen. The jig itself then bolts into the vertical face provided by the two-arm extension from the stand.

Data Acquisition System

Quantifying the impact event in a relevant manner depends on what kinds of sensors are placed on the apparatus. Section 6.3 of ASTM F355-95 outlines desired quantities and the general requirements regarding sensors associated with obtaining those quantities. The level of protection a padding sample offers is determined by how much energy it absorbs from a force. The pad does this not only by blunting its magnitude but also by spreading it over a wider area. Thus, appropriate instrumentation is needed to characterize both the force applied by the impacting rod with respect to time and the forces experienced on the area underneath the pad with respect to time. The former is quantified using a force transducer (Figure 12), while the latter is recorded using some type of pressure sensor.

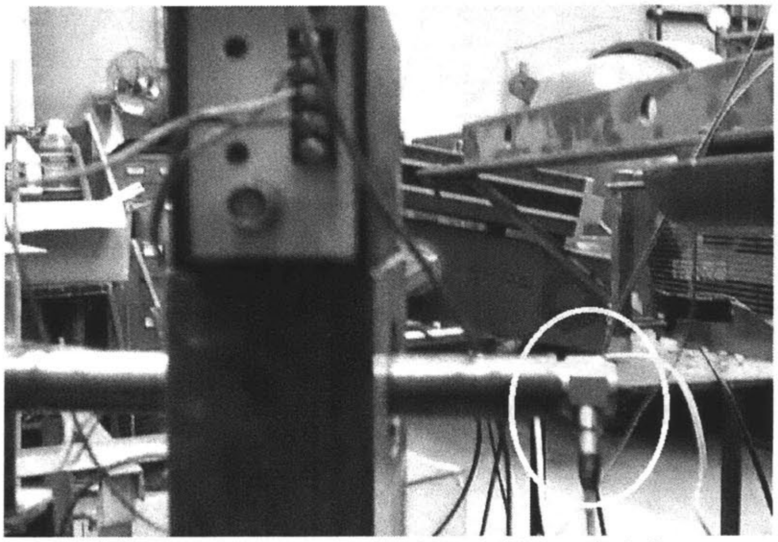


Figure 12. Force transducer sensor (lower right, encircled) at end of impactor rod. Transducer signal passes through amplifier (top left, w/wires) en route to A/D board.

While force transducers are currently a more standard instrumentation piece in industry, a Boston-area company named Tekscan makes the specialized thin electronic pressure-sensing mats (Figure 13) that are suitable for this particular project. For reference purposes, the specific documentation on each of these sensors is included with this report (Appendix A). It is important to note that there may be equally appropriate, and perhaps even more effective, sensors out on the market in comparison to the specific ones used here.

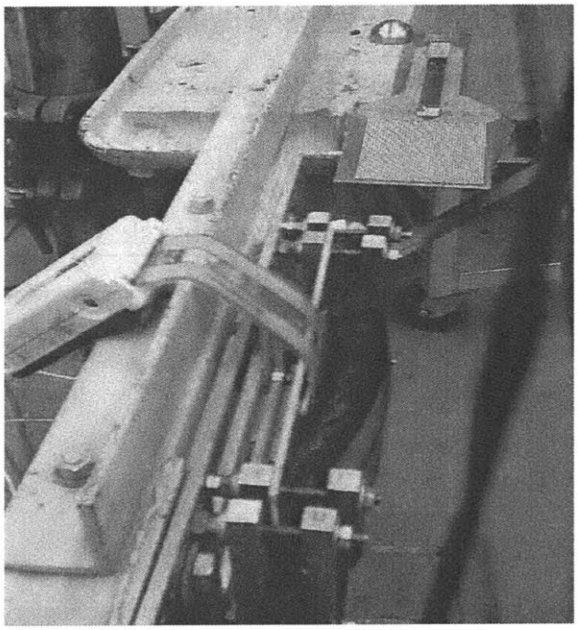


Figure 13. Tekscan pressure-sensing mat (upper right) and hardware/sensor set up behind specimen (center). (Note: I-Scan model is shown in picture, but F-Scan was actual model used in procedure.)

Unlike the impact measurement sensors, the light sensor gates on FRED are simple and robust components. Two small photo sensors (~5 mm in diameter) lie across two infrared beam cells. When the donut on the impacting rod breaks either beam, the corresponding photo sensor picks up the interruption and increases its voltage, which appears as a square wave step on the oscilloscope. Knowing the distance between the light beams (36 mm) and measuring the time between voltage rises of each step allows for calculation of the rod's velocity. The discrepancy between impact and rebound velocities in turn reveals how much of the impact energy the pad specimen absorbs.

Each of the three sensor types produces an analog signal proportional to how much load it experiences. This signal must be converted into digital form to register onto the data display systems that run on modern personal computers. Therefore, an analog-to-digital signal (A/D) board is needed in the setup. The board must have multi-channel capability for multiple sensors, polarity capability to differentiate between positive and negative force magnitude, and a fairly high sampling rate due to the rapid nature of the event. As shown in Figure 14, wires and BNC cables connect the sensors to the A/D board, which runs to a circuit card (provided in A/D board package) that installs into any standard personal computer (PC) system with available slots.

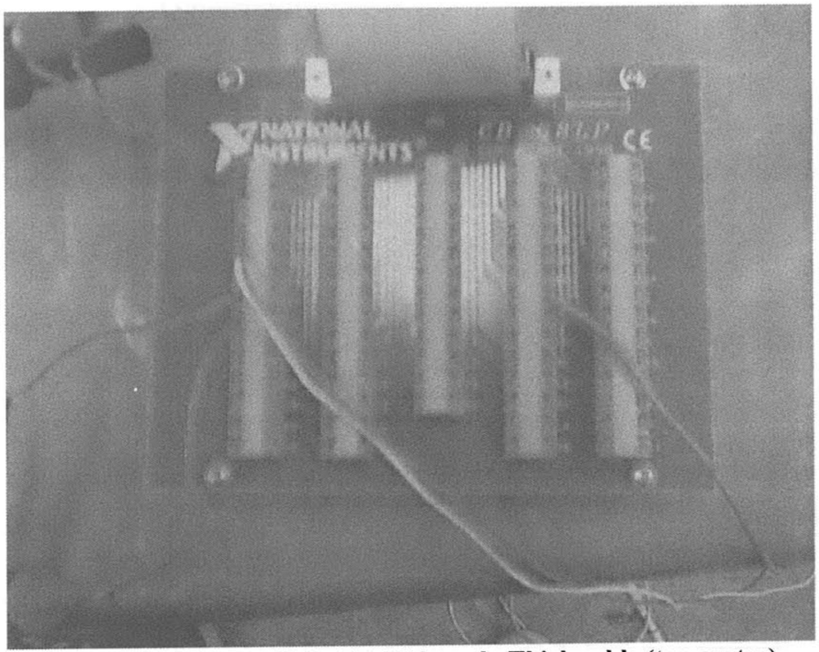


Figure 14. Analog-to-digital (A/D) board. Thick cable (top center) runs to card installed in PC. Three sets of wire leads at far left pin panel allow data to be collected from three sources: channel 0 (top, to light sensor #1), channel 1 (middle, to light sensor #2), and channel 2 (bottom, to force transducer). Wire from middle right pin panel runs to external trigger of impactor unit.

The minimum system requirements for the PC are a 486 MHz processor with 64 MB RAM, a color monitor, a keyboard, a mouse, an available I/O card slot, and a data save device (e.g. disk drive), limits which are set by the various manufacturers of the outside devices and software involved with the project. Most PC systems today easily meet these hardware requirements. The software used in data acquisition is the LabVIEW package running on a Windows NT platform, popular within the MIT Mechanical and Aeronautics/Astronautics departments for its ease of use and wide-ranging capabilities. LabVIEW's main use in this project is converting the PC into a data-logging oscilloscope, but it also allows the PC to perform more complex tasks and organize the collected data more efficiently. In addition, the Tekscan pressure sensor possesses its own hardware that connects to the parallel port of the PC and runs off its own separate software platform. The maximum sampling rate of the Tekscan unit is 169 frames per second, or one sample every .00591 seconds.

In summary, the following components comprise this particular data acquisition system:

1) Dell 486 MHz, 64 MB RAM personal computer with basic peripheral hardware;
2) National Instruments 6035E 200kS/sec 68-pin analog-to-digital signal (A/D) board and interface card;
3) Electronic measurement sensors on the apparatus, including a PCB 208B 500-lb force transducer, a Tekscan pressure sensor, a light beam/photo-sensor array for velocity measurement, and appropriate wires and clips for connecting to the A/D board;
4) LabVIEW and Tekscan software for user interface and data display/organization.

PROCEDURE

Impact testing was performed on three shoulder pad types. A pair of hockey shoulder pads and a pair of football shoulder pads, both off-the-shelf products from well-known companies, were tested against a new prototype padding (Figure 15) whose basic design allows it to be used in either sport. Rectangular samples of area 4" x 9" were cut from each type of pad (Figure 16) for placement in the specimen holding jig. All specimens were conditioned in accordance with Section 9 of and tested in line with Section 10 of ASTM F355-95.

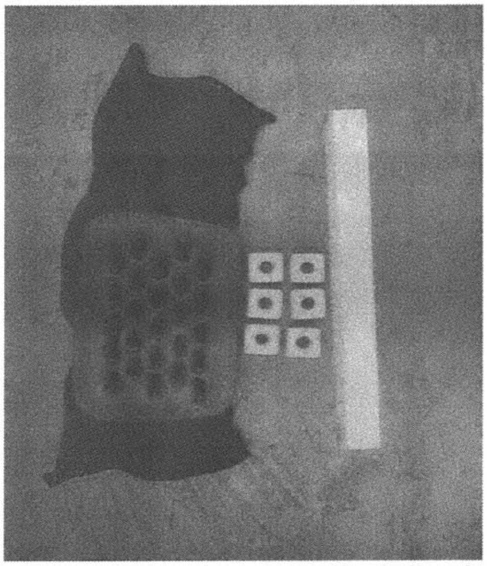


Figure 15. Prototype hockey/football pad for testing. Specimen consists of 1" holed foam cubes (right) separated into individual slots and sewn together into breathable fabric matrix. Rigid composite panels (left, honeycomb), attached by Velcro, cover areas of high impact. Unlike existing shoulder pads, prototype is a front-zip long-sleeve jacket, offering more protective area coverage.

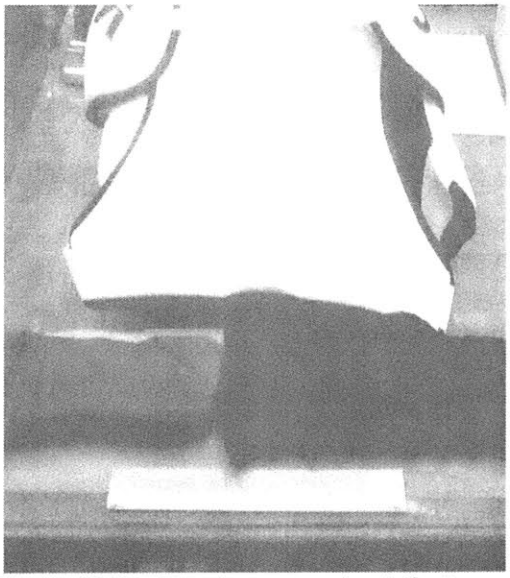


Figure 16. Pad specimen samples A (bottom left, football only), B (bottom right, hockey/ football), and C (top, hockey only). Note that specimen C has not yet been cut to fit jig.

As mentioned, the impactor unit of FRED strikes the specimen with a velocity proportional to how far the spring of the striker unit is compressed. This is on account of the law of conservation of energy, which mandates that the potential energy in the spring manifests itself entirely in the kinetic energy of the impactor unit (minus negligible energy lost in the form of sound):

$$\frac{1}{2}k_{spring}x^2 = \frac{1}{2}m_{rod}v_{rod}^2 \qquad (1)$$

Given a fixed mass for the impactor unit, Equation (1) can be manipulated to relate the impact velocity to the spring compression distance by a constant of proportion. Thus, a logical first step in the procedure was to calibrate the striker unit, eliminating the need to take velocity data during every trial. Figure 17 illustrates this step.

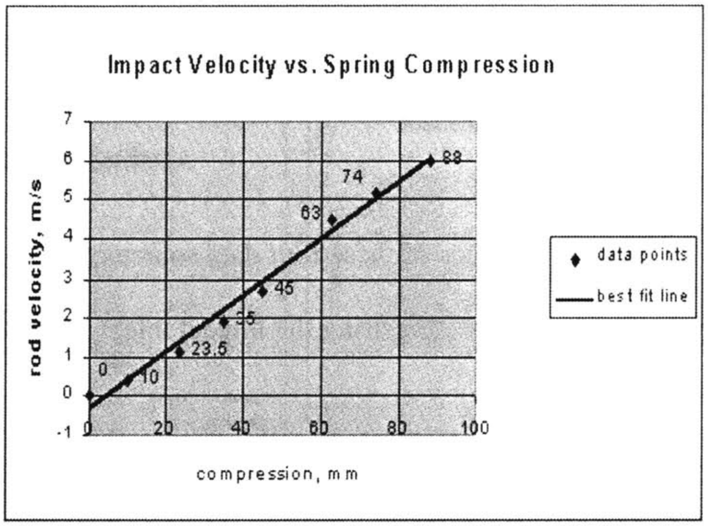


Figure 17. Calibration of striker unit spring of FRED.

Before preparing FRED to deliver the impact, the next step was to check all sensors to ensure they were functional, properly fastened to the apparatus, and registering signals on the LabVIEW interface. Next, both the LabVIEW software and Tekscan software were readied for data collection. This step involved setting sampling rates, triggers, timing parameters, display parameters, and designations for the different sensor signals. Finally, each sensor signal was calibrated to relate the voltage readout on the PC to the particular quantity being measured by the sensor.

With all preliminary measures complete, FRED was then put into operation through the various steps described in the apparatus section of this project. With the primary purpose of demonstrating the application of the procedure, one trial of constant impact velocity was performed on each of the three shoulder pad specimens. The following quantities were sampled and recorded on each data trial:

1) Output voltage waveforms of each light sensor with respect to time;
2) Output voltage waveform of the force transducer with respect to time;
3) Graph of pressure with respect to time and location on the Tekscan sensor;
4) Graphs of both peak force and peak pressure with respect to time experienced by the Tekscan sensor.

Measurement of characteristics of these four data sources, along with subsequent calculations, yielded information for comparing the impact integrity of the three shoulder pad specimens.

RESULTS

Even though only one set of data was taken for each trial, the procedure was repeated several times for each specimen to observe the results and confirm the accuracy of the particular data presented in this section. Figures 18 and 19 illustrate the two wave types generated by each experimental trial. From trial to trial the output waveforms from the transducer or the light gate were generally the same, with variations only in magnitudes. The x-axis of each graph only relates sequence of samples taken by LabVIEW data recorder (via the A/D board), but knowing the sampling rate set for each particular trial allows for calculation of time within an accuracy equal to the reciprocal of the sampling rate (i.e. 0.1% for Figure 19).

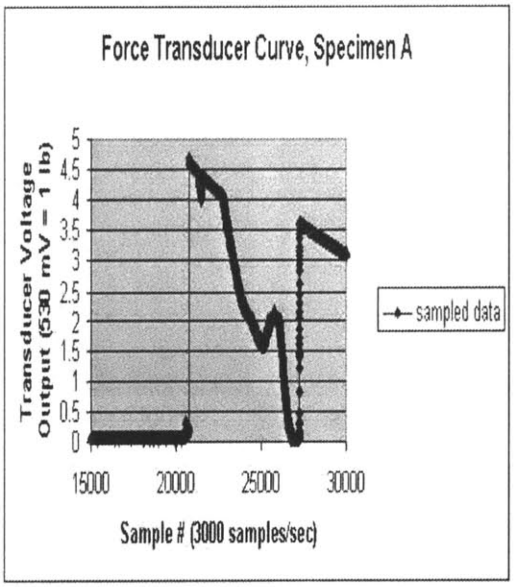


Figure 18. Sample voltage output waveform from force transducer.

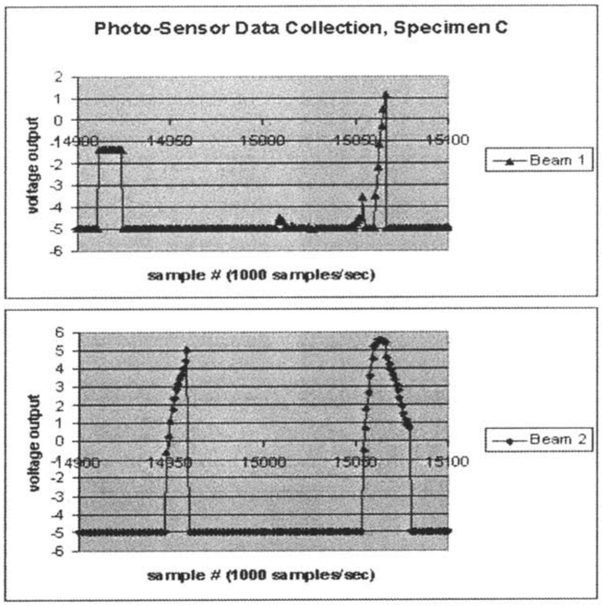


Figure 19. Sample voltage output waveforms from light gates.

Figures 20 through 24 illustrate the results and calculations of each individual impact trial. At the top of each data sheet are numerical values, both measured and calculated, for quantifying the particular trial and comparing it to the others. At the bottom is a frame-by-frame look at the impact event reaction from underneath the pad specimen, courtesy of the Tekscan pressure sensor. The same sensor also provides the data for Figures 24 and 25, which offer a cursory qualitative comparison of the degree of protection offered by the pad specimens.

Specimen: A (football only)

Experimentally Determined Quantities:

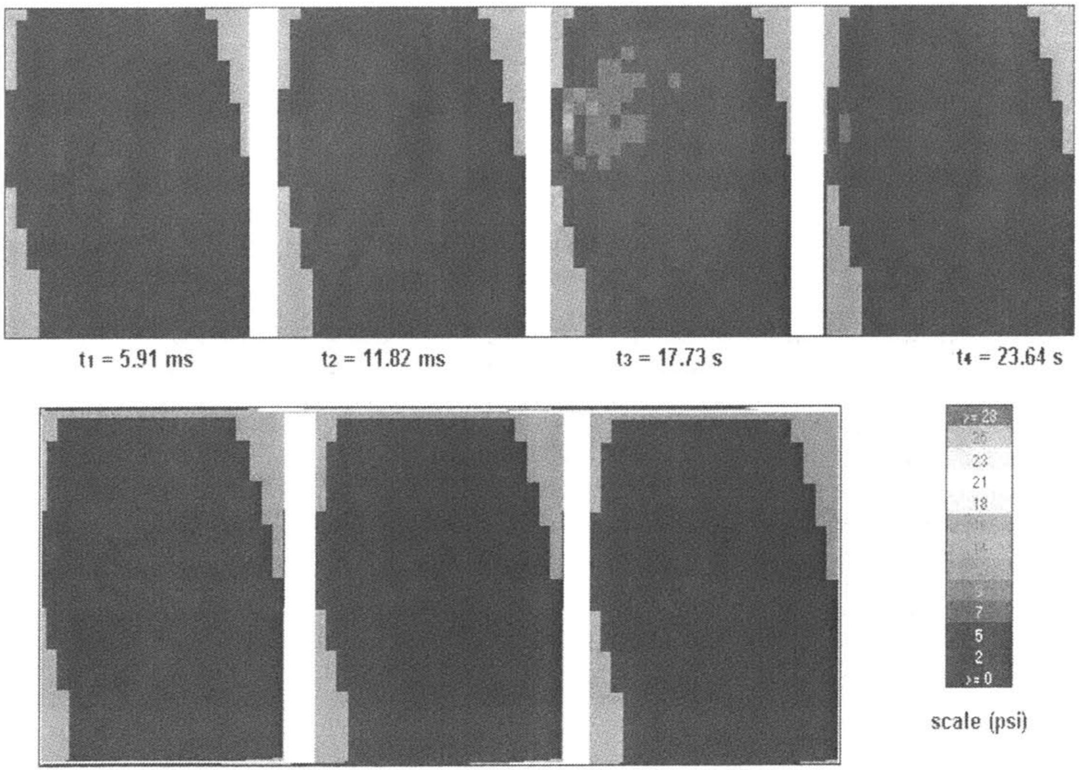
Striker Unit Spring Compression:	55.000 mm	0.140 in	
Measured Incoming Velocity of Impact Rod:	2.700 m/sec	8.858 ft/sec	
Maximum Force Measured by Transducer at Impact:	39.317 N	8.845 lbf	
Time of Force Action on Specimen:	5.470E-02 sec*		
Contact Area of Force Underneath Pad:	66.064 sq cm	10.240 sq in	166 % of impact area
Dispersion Diameter of Force Underneath Pad:	10.541 cm	4.150 in	148 % of impact diameter
Time of Pressure Sensation Underneath Pad:	4.730E-02 sec**		
Rebound Velocity of Impact Rod:	1.187 m/sec	3.894 ft/sec	
Mass of Hockey Puck	0.170 kg	0.374 lb mass	
Mass of Impacting Rod	1.393 kg	3.064 lb mass	

Calculated Quantities:

Estimated Impact Force on Specimen:	44.116 N	9.925 lbf
Estimated Impulse to Specimen:	2.413E+00 N-sec	5.429E-01 lb-sec
Estimated Pressure Applied to Specimen:	11.114 kPa	1.612 psi
Estimated Impulse to Surface Underneath Specimen:	7.532 N-sec	1.695 lb-sec
Total Energy Absorbed By Pad:	5.881 J	

**Due to signal aliasing, actual value may be smaller. Maximum error is 0.61%.*
***Due to Tekscan resolution limitations, actual value is larger. Maximum error is 11.1%.*

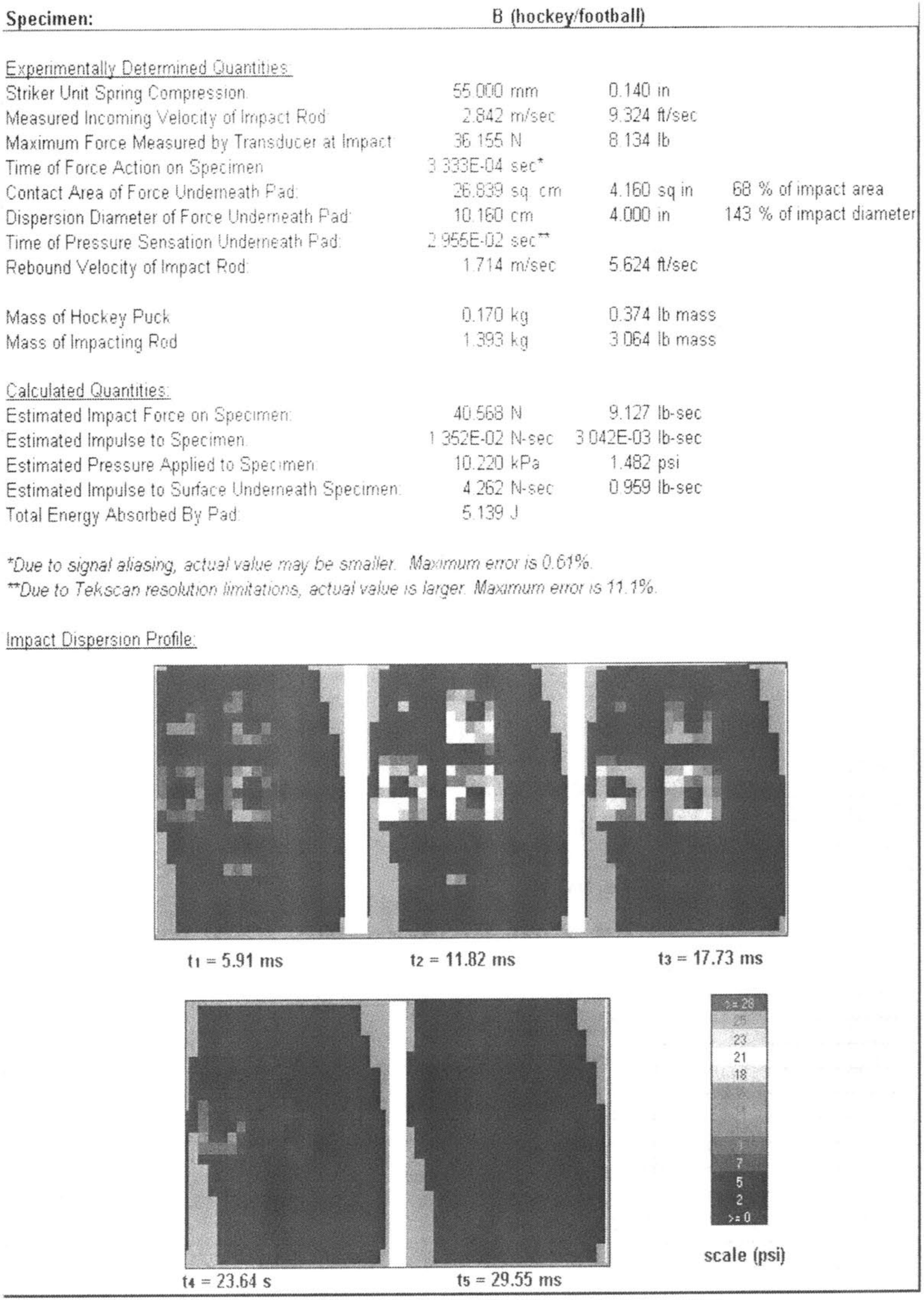
Impact Dispersion Profile:


t1 = 5.91 ms　t2 = 11.82 ms　t3 = 17.73 s　t4 = 23.64 s

t5 = 29.55 ms　t6 = 35.46 ms　t7 = 41.35 ms

scale (psi)

Figure 21. Experimental data collected for Specimen A.



Specimen: **B (hockey/football)**

Experimentally Determined Quantities:

Striker Unit Spring Compression:	55.000 mm	0.140 in	
Measured Incoming Velocity of Impact Rod:	2.842 m/sec	9.324 ft/sec	
Maximum Force Measured by Transducer at Impact:	36.155 N	8.134 lb	
Time of Force Action on Specimen:	3.333E-04 sec*		
Contact Area of Force Underneath Pad:	26.839 sq. cm	4.160 sq in	68 % of impact area
Dispersion Diameter of Force Underneath Pad:	10.160 cm	4.000 in	143 % of impact diameter
Time of Pressure Sensation Underneath Pad:	2.956E-02 sec**		
Rebound Velocity of Impact Rod:	1.714 m/sec	5.624 ft/sec	
Mass of Hockey Puck	0.170 kg	0.374 lb mass	
Mass of Impacting Rod	1.393 kg	3.064 lb mass	

Calculated Quantities:

Estimated Impact Force on Specimen:	40.568 N	9.127 lb-sec
Estimated Impulse to Specimen:	1.352E-02 N-sec	3.042E-03 lb-sec
Estimated Pressure Applied to Specimen:	10.220 kPa	1.482 psi
Estimated Impulse to Surface Underneath Specimen:	4.262 N-sec	0.959 lb-sec
Total Energy Absorbed By Pad:	5.139 J	

**Due to signal aliasing, actual value may be smaller. Maximum error is 0.61%.*

***Due to Tekscan resolution limitations, actual value is larger. Maximum error is 11.1%.*

Impact Dispersion Profile:

Figure 22. Experimental data collected for Specimen B.

Specimen Designation: **C (hockey only)**

Experimentally Measured Values:

Striker Unit Spring Compression:	55.000 mm	0.140 in	
Measured Incoming Velocity of Impact Rod	2.769 m/sec	9.085 ft/sec	
Maximum Force Measured by Transducer at Impact:	38.512 N	8.664 lbf	
Time of Force Action on Specimen:	3.333E-04 sec*		
Contact Area of Force Underneath Pad:	52.387 sq cm	8.120 sq	132 % of impact area
Dispersion Diameter of Force Underneath Pad:	9.220 sq cm	3.630 in	130 % of impact diameter
Time of Pressure Sensation Underneath Pad:	2.955E-02 sec**		
Rebound Velocity of Impact Rod:	1.714 m/sec	5.624 ft/sec	
Mass of Hockey Puck	0.170 kg	0.374 lb mass	
Mass of Impacting Rod	1.393 kg	3.064 lb mass	

Calculated Quantities

Estimated Impact Force on Specimen:	43.212 N	9.722 lbf
Estimated Impulse to Specimen:	1.440E-02 N-sec	3.241E-03 lb-sec
Estimated Pressure Applied to Specimen:	10.886 kPa	1.579 psi
Estimated Impulse to Surface Underneath Specimen:	12.799 N-sec	2.879 lb-sec
Total Energy Absorbed By Pad:	4.730 J	

*Due to signal aliasing, actual value may be smaller. Maximum error is 0.61%

**Due to Tekscan resolution limitations, actual value is larger. Maximum error is 11.1%.

Impact Dispersion Profile:

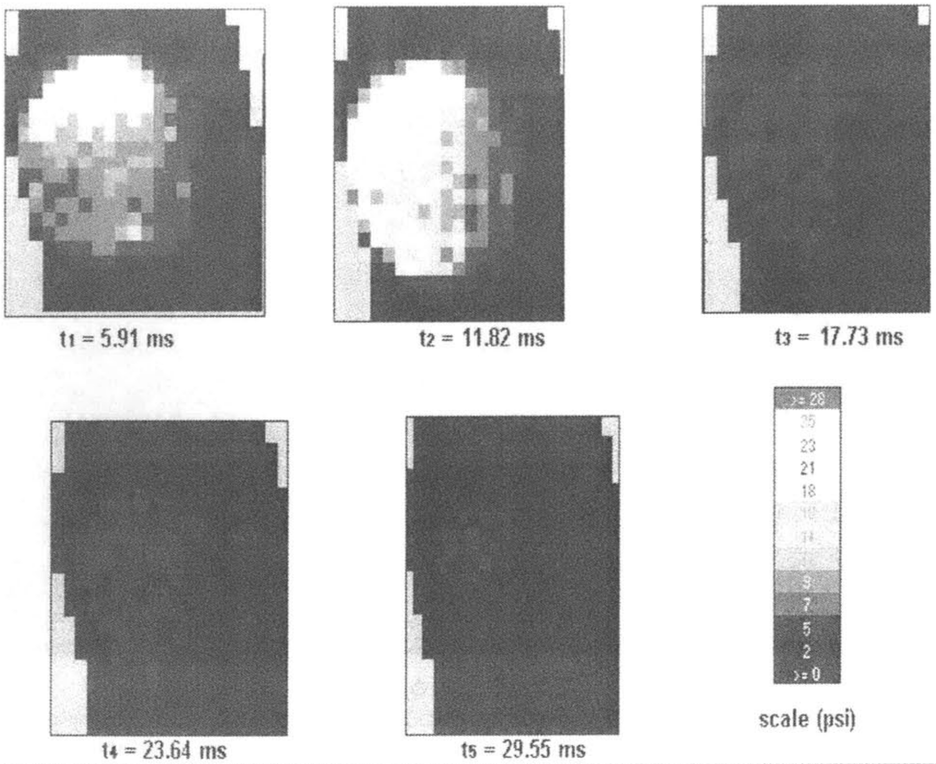


Figure 23. Experimental data collected for Specimen C.

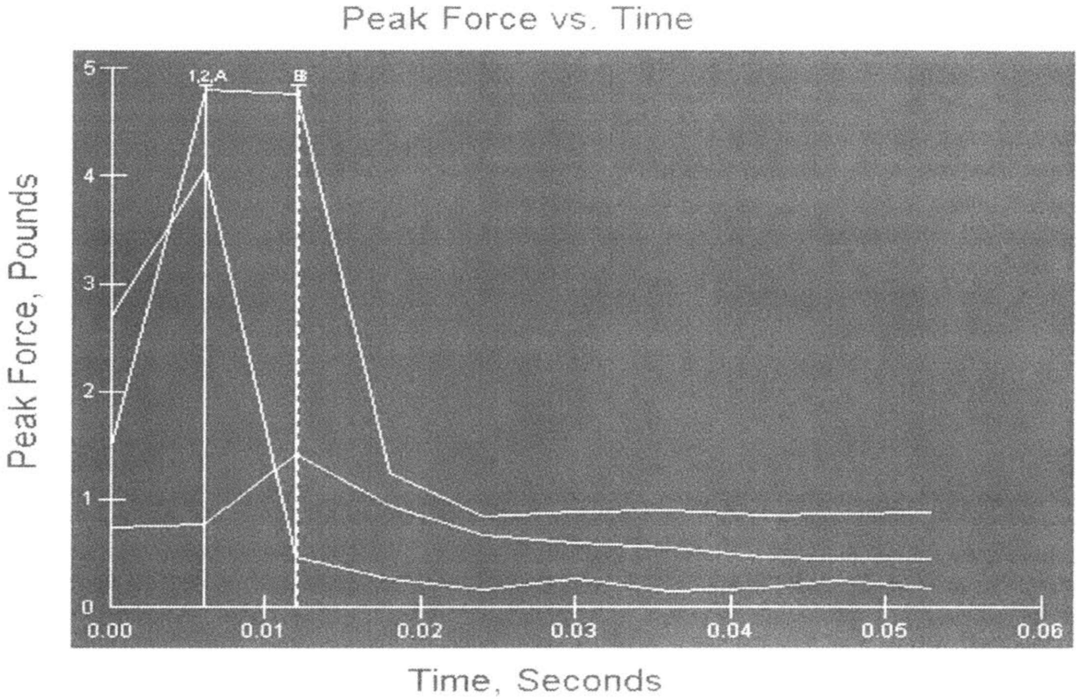


Figure 24. Peak force on Tekscan sensor with respect to time for Specimen A (starting point ~0.7 lb), specimen B (starting point ~1.5 lb), and Specimen C (starting point ~2.8 lb). Note that these contours are based on only five data points.

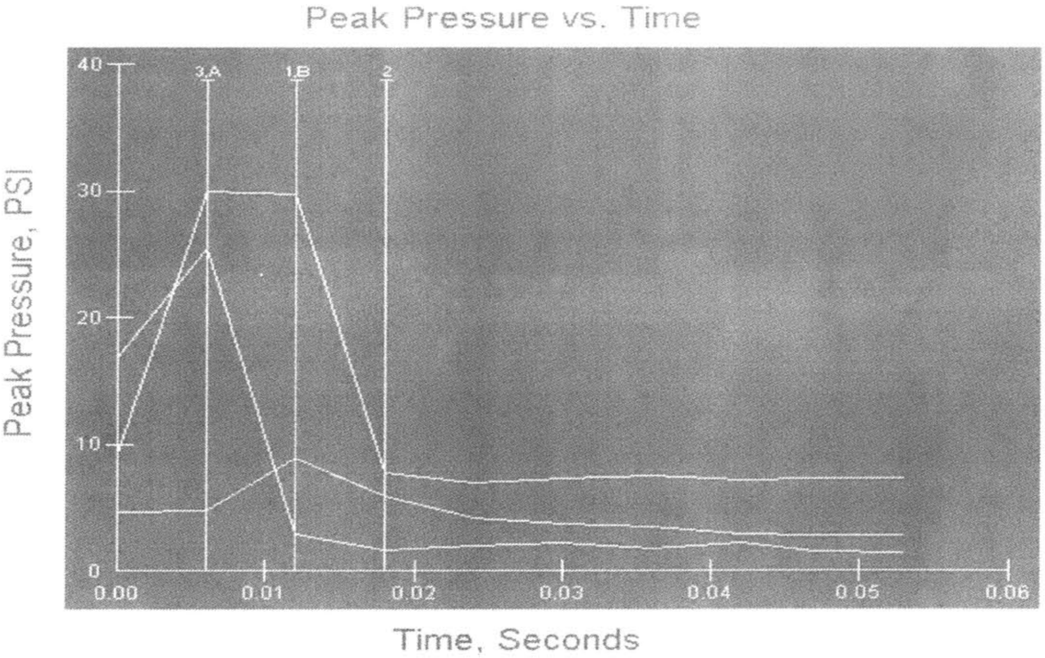


Figure 25. Peak force on Tekscan sensor with respect to time for Specimen A (starting point ~5 psi), specimen B (starting point ~20 psi), and Specimen C (starting point ~10 psi). Note that these contours are based on only five data points.

DATA ANALYSIS / EXPERIMENTAL CONCLUSIONS

Force Transducer Data

The PCB 208B force transducer, a cylinder-shaped sensor, produces an output voltage linearly proportional to the force it experiences on either of its flat faces. The calibration sheet in Appendix A shows that for this specific unit the proportion is 530.9 mV/lb, with compression producing a positive voltage. The charge amplifier is on hand to amplify small-load voltages that might otherwise be masked by signal noise, but it was discovered that it was not necessary for the force magnitudes experienced in these trials. (In fact, any gain from the amplifier produced saturation in the signal, which resulted in the curve being truncated at the 10 V input limit of the A/D board.)

As a result, from graphs such as the one in Figure 18 one divides the y-axis voltage values by .5309 to find the force values with respect to sample number progression. Each sample corresponds to an instant in time, so dividing the difference in sample numbers by the user-defined sampling rate (1-3kS/sec to avoid aliasing) yields the time difference between data points.

All curves obtained in this impact test carry the same form as that of Figure 18: the compression force starts at zero, breaks upward sharply to its peak, levels toward zero with minor perturbations, then shoots up once more before leveling to zero, all within several tenths of a second. Each of these occurrences can be explained by observing the motion of the impact rod as it strikes the specimen, bounces back off the striker unit, and is stopped by the catch. The waveform characteristic of the most significance is the initial peak, which is the force imparted to the specimen by the rod. Also of interest is the time taken to reach that peak. Together these two quantities determine impulse, which is an index of how damaging an impact event can be. Impulse is defined as the area under the force-time curve.

The force experienced at the transducer is not equal to the force experienced at the point of impact with the pad. This is because in this case, the hockey puck tup is not negligible in comparison to the mass of the rod. Safely assuming the force transducer is of negligible mass compared to the rod and puck, the impact force to the specimen is calculated as follows:

$$F_{impact} = \left(\frac{m_{rod} + m_{tup}}{m_{rod}}\right) F_{transducer} \tag{2}$$

Light Gate Data

As shown in Figure 20, the photo sensors are working correctly when distinct voltage steps are present and in the following sequence: first beam, second beam, second beam again, first beam again. Within this timespan, the impactor strikes the specimen in between the consecutive breaks of the second beam. So, the time difference between the first voltage step-downs (high-to-low signal travel shown as vertical line in graph) of beams 1 and 2 is used to calculate the rod impact velocity. (Because of noticeable, albeit minor, variations present in Figure 18, it was decided to record the actual impact velocity at each trial rather than using values from the striker unit calibration.) Similarly, the voltage step-up (low-to-high signal travel) time difference is used to calculate the rod rebound velocity. Recall that velocity is beam-to-beam distance, in this case 36 mm, divided by time. Recall also that time difference is difference in sample numbers divided by sampling rate.

Because the massive testing rig (+250 lb) is essentially immovable, it can be assumed that the pad absorbs any and all energy lost by the impact rod. Therefore, the energy absorption capability of the pad is known once the initial and final kinetic energies of the rod are calculated (KE=0.5*m*v_). Given the constant mass of the tup and rod throughout the impact event, the light gates fill in the final blank by providing the impact and rebound velocity measurements.

Pressure-Sensing Mat Data

The Tekscan F-Scan pressure sensor and its corresponding software provide the bulk of the data for qualitative comparison of specimens. Although its sophisticated technology is rather impressive and its capabilities are wide-ranging, the Tekscan device possesses a major weakness in its inability to measure force with the precision mandated by most engineering applications. This shortcoming is one that Tekscan is admittedly aware of and is working to improve on in the future. The F-Scan does report with remarkable accuracy both the relative force magnitudes across the mat and the local areas of the mat experiencing loading.

In addition to contributing the frame-by-frame illustrations of the impact event at the bottom of Figures 21 through 23, Tekscan also provides a direct numerical value of the force contact area experienced underneath the pad. From the graphs themselves, one can measure the impact dispersion diameter and the elapsed time of the pressure sensation. The former is defined as the maximum distance between pixels reporting loading in any of the frames, while the latter is determined by multiplying the Tekscan sampling rate by the number of frames that report appreciable loading.

It should be mentioned that another limitation in data collection was imposed by the maximum achievable sampling rate for the particular Tekscan hardware unit used in this procedure. Sampling rate was restricted to 169 frames per second, or a frame every 5.91 ms. Thus, as evidenced by the first frame in each data set, for these rapid impact events, the force profiles changed more quickly than the sensor could capture and display the data.

As a result, the actual time of pressure sensation is definitively greater than what the frame evidence reports in the figures, and without being able to increase resolution, one could only make an educated estimate of this quantity by interpolating the data that the system did capture. According to Tekscan, this resolution problem is solvable by using an upgraded hardware system currently on the market. Without the resources available to purchase that upgrade, the accuracy of the data for the project was slightly hampered. Still, the graphs provide valuable qualitative insight into understanding the effects of the impact event underneath the pad.

Implications of Data

Comparison of the data gathered from the three trials reveals both qualitatively and quantitatively that Specimen B, the prototype padding, lies in between the control specimens A and C in terms of impact protection. The estimated impact forces for each trial being similar (only 8% difference reported between trials), Specimen A absorbs more impact energy than the other two, disperses it over a larger impact diameter, and blunts the force by extending it over a larger time. Specimen B is superior to Specimen A in limiting the impulse delivered to its underlying surface and comparable in dispersion diameter and absorbed energy. Specimen C is clearly the less protective model, for although it disperses energy adequately, it absorbs less energy, allowing appreciably larger impulses to be experienced by the underlying surface. Looking at the dispersion profile charts, it is observed that Specimens B and C experience more critical pressure values than Specimen A, but Specimen B arranges these critical pressures in its characteristic pattern and spreads them out over a wider range.

The results are consistent with expectations prior to testing. Specimen A is thicker and springier to the touch, whereas Specimen C is lighter, thinner, and more rigid. Specimen B, however, is even lighter and more flexible than Specimen C, yet offers both more impact protection and more potential for area coverage than Specimen C. Further development is needed to develop Specimen C to the protective levels for football characterized by Specimen A, but it is no surprise that Specimen B has been met with rave reviews by those professional and college hockey players who have had access to a prototype for use in competition.

One step that would help this impact testing data move forward in a more practical direction is finding out what pressure values experienced underneath the pad constitute the threshold for pain in competing athletes. Specimen A limits underlying surface localized pressures to 14 psi, while Specimen C extends localized pressure readings to 35 psi. It is interesting to point out here that Specimen A is the football pad, whereas Specimen C is a popular professionally-endorsed pad for hockey, where impact forces are generally much higher due to greater velocities from skating as opposed to running. It may very well be that the pain threshold occurs at a considerably higher localized pressure than 35 psi, making the protective benefits of Specimen A over Specimen C a moot point. If this were the case, athletes would then choose protective padding based how well it enhances (or does not detract from) their abilities in the hockey rink or on the football field.

With only one trial taken for each specimen, the claims made by the data presented here are limited in scope. One would do well to collect more data to corroborate the comparative implications of this singular set of impact testing trials. Repeating the procedure while introducing closely monitored variations is the simplest and most direct of gathering additional data. More creative suggestions on how to introduce such variations appear in the following section outlining development toward a standard testing method, which is the focus of this thesis project.

PATH TO A STANDARD (FURTHER STEPS)

The impact testing procedure completed in this project is concise and of primary importance to validating protective padding, but it tells only the first part of the entire story. In the interest of time, the chief concern was demonstration of the testing procedure, data collection methods, and data presentation. However, the scope of this exact procedure can, with minor adjustments, be increased to provide much more supporting data to its user. In addition, the impact testing process as a whole should undergo more refinements to simulate the conditions experienced by hockey/football shoulder pad wearers. Finally, several other procedures should be added to this one before considering development into a worthy standardized testing method for football/hockey protective padding.

Expanding Scope of Impact Testing Using FRED

With regards to the current experimental setup, this apparatus possesses numerous other options for data collection that have gone unused in the interest of time and clarity. Utilization of these options may provide more data in support of the impact integrity of one shoulder pad over another. Therefore, it is important to point out such options, which showcase the usefulness of FRED despite its simplicity.

It is mentioned earlier in this document that the impacting rod ends, or tups, are interchangeable via a threaded rod (Figure 12). This feature allows for simple alterations to impact mass, and thus impact velocity. Employing this feature invites more educated comparison between the impact absorption features of the pads. For example, one pad may absorb impact more effectively than another at higher velocities, but at lower velocities the opposite is true, due to one pad's spring constant being nonlinear in nature.

Similarly, there may exist the possibility that at lower masses two samples spread the impact equally effectively, yet at higher masses extra force concentration causes differing dispersion results.

Changing the shape and material of the tups may reveal additional information about force dispersion patterns among pad specimens. Given a fixed mass, the tup shape plays a role in how the contact force reacts with the pad, so it is not unreasonable to expect different force dispersion areas will result from different tup shapes. Furthermore, the tups themselves absorb impact energy, which is seen in the rebound velocity of the impact rod. A tup fashioned out of a more energy-absorbent material than the aluminum used in this procedure is another possible source of varying results from sample to sample.

A more time-consuming alteration to FRED, but likewise one FRED allows for, is the switching of the energy-storing spring on the striker unit. Currently at FRED's disposal are two other thick-coil springs of different size (Figure 13), whose presence indicates that spring changes were in fact envisioned by FRED's designers. Changing the spring is an option should a desired impact velocity lie outside the range of the spring in place.

With these options in mind it is foreseeable to run using this very apparatus a testing procedure that can mimic every impact event to shoulder pads in the sports of football and hockey. First, more focused research must be performed on velocity ranges for footballs, pucks, stick slashes, and players into boards and each other. Next, springs must be built or ordered to achieve these velocities, and all other parts of FRED (e.g. magnets, winch) must be checked to ensure they still hold up when these new springs are compressed. Finally, new tups with identical interfacing must be built in the shape and material of these projectiles. This process, although time-consuming, would provide invaluable data for shoulder pad manufacturers to answer the questions of their consumers.

Scaling Impact Testing to Biomechanics and Kinesiology

Despite its efficacy and flexibility, the current impact testing apparatus and procedure still invites major overhaul to solidify consumer credibility. This overhaul focuses on replacing the specimen holding assembly with a sort of mannequin assembly, so that the shoulder padding may be tested in an as-sold state, and the impact forces may be localized to specific regions and structures of the human body in a manner similar to automotive industry safety testing. The following paragraphs offer suggestions on working toward this attractive end goal.

In the research phase of this project, over 50 universities across North America were contacted in order to request information from biomechanics laboratories regarding impact testing procedures on humans (Appendix B). Although no useful responses were received, the efforts did discover resources and knowledgeable faculty across the continent. Several responses expressed strong interest in the outcome of the project and offered their resources for future development. These resources would have to be utilized to carry out this task.

The first step is to design and create a larger version of FRED. This is because more massive tups are needed to impact the specimen. Creating a model of the shoulder, which often delivers the blow in football and hockey, is a difficult task, and in contacting universities it was found that limited research has been done on it. However, a standard headform, which is another likely source of impact, has been modeled by the American National Standards Institute (ANSI), and several ASTM standards, including F355-95 (Section4.2.3), make use of it in their testing method. Thus, this headform, with a football or hockey helmet strapped to it, makes the ideal tup for impact testing. To incorporate it requires scaling up in size of the impacting rod and sensors and a more secure fastening method to the impacting rod. From this requirement naturally follows the need for a proportionally larger striker unit for energy transfer, and although the basic components and functions of the striker unit will be the same, larger elements again necessitate reevaluation for safety purposes.

Modifying the specimen holding assembly into a human form simulating actual hockey/football playing conditions is the next challenge. Several biomechanics laboratories have done mathematical and physical modeling of parts of the human anatomy, and crash test dummies from the automotive industry provide another starting point for gathering information. The end goal is to create a life-size physical model of a human torso onto which a football/hockey shoulder pad may be worn in standard fashion. In addition to its size, issues to consider when building this humanoid testing rig are its mass, density, and material rigidity; its secure mounting to a fixed surface; where on the rig to place the sensors; and how to conduct an informative testing procedure. With regards to the latter two, a study on shoulder pads conducted at Kansas State University[2] may provide greater insight.

Using Tekscan pressure mats for data collection from this humanoid testing rig is desirable, but currently these sensors are more suited to flat surfaces. One possibility is

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[2] L. Noble, H. Walker, R. Dorgan, D. Deppen. *Evaluation of Football Shoulder Pads.* Kansas State University, 1996.

to affix smaller pressure sensors at more points on the rig. However, a multitude of sensors would require extensive, and perhaps obtrusive, wiring, not to mention an equally capable, and thus more expensive, A/D system. Research and development of a more optimal sensor and data collection package is needed. It should be mentioned, though, that the Tekscan company is the logical frontrunner for contracting this task.

Taking the expansion of specimen holding assembly concepts even further, one could eventually look into placing this humanoid torso onto a movable base, with the aim of taking the impact event simulation to its highest level. In football and hockey, very rarely are players stationary, either before or after contact. Giving the testing rig one or more degrees of freedom allows one to replicate player movement toward impactor before hit and recoil from impactor after hit. Of course, before deciding on such a complicated feature exhaustive cost/benefit analysis must be performed to ensure its usefulness.

Finally, research efforts need to focus on developing mathematical models for impact loads that result in bruising, tissue damage, sprains, joint dislocation, and bone breakage. It is adverse physiological responses such as these that the shoulder pad seeks to prevent from happening. Therefore, more information should be gathered on these force magnitudes, their timespans, their characteristic waveforms, their areas of interaction, and how they translate into the pressures felt by the human body. This task is more suitable to biomechanics and kinesiology specialists, but these specialists must receive constant input from the mechanical engineer regarding the specifics of the mechanism delivering the force.

Range of Motion Studies and Testing Procedure

As a product's protective capability increases, the range of movement and comfort the product provides generally decreases. For athletes in contact sports, speed, flexibility, and capacity for unrestricted natural motion are essential to gaining an edge over the opponent, and oftentimes it is the slightest edge that winds up producing the margin of victory. Because a shoulder pad aims for maximum mobility in addition to maximum protection, its integrity evaluation should not be based solely on impact absorption and dispersion characteristics.

An essential part to any standardized test method for shoulder pads is some procedure for assessing range-of-motion restrictions to its wearers. The basic component of this assessment is weight, both overall and distributed throughout subregions of the pad. More weight means greater inertia, or resistance to movement. Thus, greater total weight diminishes running/skating speeds and lateral movement, and greater distributed weight hinders the quickness of motions such as swinging a hockey stick, raising arms to catch a pass, or rotating one's torso to change directions. One recommendation to include in a standard is to rate shoulder pads on a 1-5 scale on total weight, weight per unit area (or unit volume), and weight distribution over subregions, such as, for example, trapezius, clavicle, deltoid, and chest areas.

In addition to weight, the shape of the pad assembly can also be a source of limitation to motion. For rigid, non-compressive materials (e.g. hard plastics) that comprise shoulder pad structures, hinges, snaps, and straps connect adjacent panels to ensure coverage of critical areas. Unlike bendable foams, these panels do not conform to the contour of the body and can therefore impede natural motion depending on their orientation. This is not to say that those flexible materials of a shoulder pad cannot be obtrusive either. Layers of foam, especially thicker, denser ones, also counteract movements of the upper body, albeit to a lesser degree than the rigid elements.

The obvious process in formulating a range-of-motion test for shoulder pads is to determine an individual's maximum degree of movement without the pads, compare those results to his or her maximum degree of movement wearing the pads, and create some kind of quantitative sliding scale based on any relevant biomechanics research and numerous experimental repetitions. Less obvious and much more difficult is explicitly defining a sensible apparatus and method that measures "degree of movement." Should this arduous task be resolved, the final step is to universalize the entire procedure for football/hockey players of all sizes.

One suggestion for implementing this process is to create some sort of wall chart with numbered markings along an ideal path of motion. An individual stands upright against the chart and takes his arms through this path, attempting to reach and touch each numbered point. The individual then repeats the exercise wearing the shoulder pads, and the results are compared. For paths not in a vertical plane of motion, the nature of this standard chart may be replicated by suspending numbered spheres from above via a string. The individual would then stand in the middle of the spheres and repeat the process, being evaluated on a sliding scale based on how many and which spheres he or she can touch.

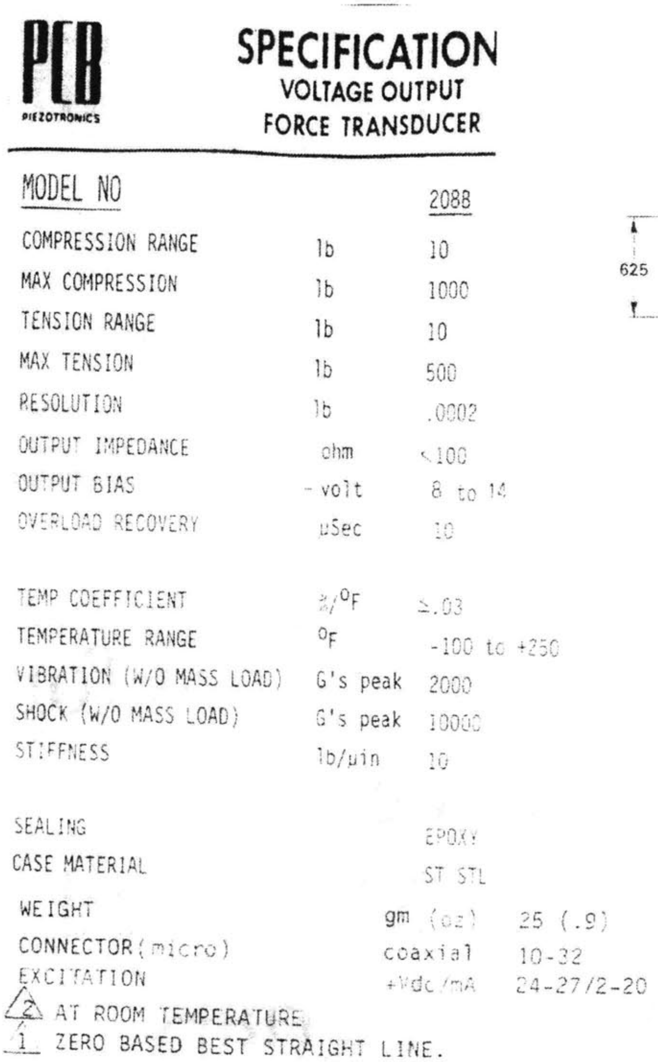
Another plausible idea for evaluation is to film specific hockey/football motions with and without shoulder pads using a high-speed camera. Filming would occur against a special backdrop possessing numerous easy-to-read position markers. These markers would provide a quantitative basis of analysis when comparing two movies of the same motion (e.g. a slap shot) with and without the shoulder pads. Frame-by-frame breakdown of such movies would eventually allow for comparative grading of shoulder pad prototypes based on how much freedom of motion they provide.

Finally, in addition to impact and range-of-motion testing procedures, any proposed shoulder pad standard should also include a method for evaluating a product's comfort and wearability. It may be argued, and with reason, that personal preference of the athlete is the overriding factor in the determination of this characteristic. Be that as it may, all subjective decisions are based on some process of data gathering and objective analysis, and there certainly exists the opportunity to test for quantitative data relevant to comfort and wearability. Methods to do so include monitoring body temperature underneath the padding during and after activity, gauging moisture buildup and absorption characteristics of the padding, and measuring the amount of friction the padding causes against the skin.

In making strides toward a concise standardized test method for shoulder pads, one must remember to restrict focus to the three priorities of all protective equipment, in order of importance: protection, freedom to move, comfort. From the iron breastplate of 2000 years ago to the chain mail of 1000 years ago to the EVA foams of today, technology has constantly evolved the shoulder pad in an effort to maximize any or all of those three qualities. Reaching legitimization of an appropriate standard is fundamental to ensuring technology continues to do wonders in protecting the athlete-warriors of the future.

Appendix A:

Supplemental Information for Force Transducer and Pressure-Sensing Mat Used In Experimental Trials



PCB
PIEZOTRONICS

SPECIFICATION
VOLTAGE OUTPUT
FORCE TRANSDUCER

MODEL NO		208B
COMPRESSION RANGE	lb	10
MAX COMPRESSION	lb	1000
TENSION RANGE	lb	10
MAX TENSION	lb	500
RESOLUTION	lb	.0002
OUTPUT IMPEDANCE	ohm	<100
OUTPUT BIAS	- volt	8 to 14
OVERLOAD RECOVERY	μSec	10
TEMP COEFFICIENT	%/°F	≤.03
TEMPERATURE RANGE	°F	-100 to +250
VIBRATION (W/O MASS LOAD)	G's peak	2000
SHOCK (W/O MASS LOAD)	G's peak	10000
STIFFNESS	lb/μin	10
SEALING		EPOXY
CASE MATERIAL		ST STL
WEIGHT	gm (oz)	25 (.9)
CONNECTOR (micro)	coaxial	10-32
EXCITATION	+Vdc/mA	24-27/2-20

2 AT ROOM TEMPERATURE
1 ZERO BASED BEST STRAIGHT LINE.

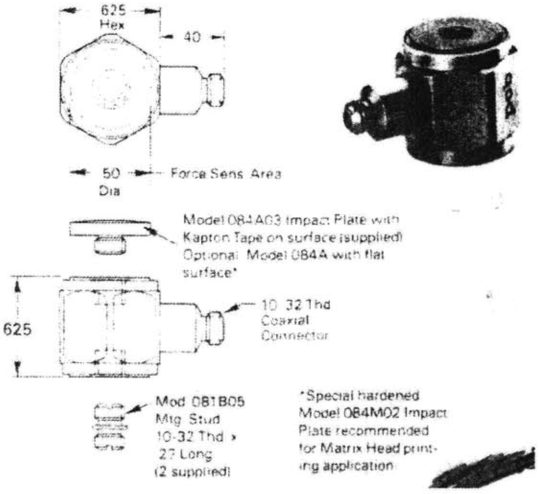
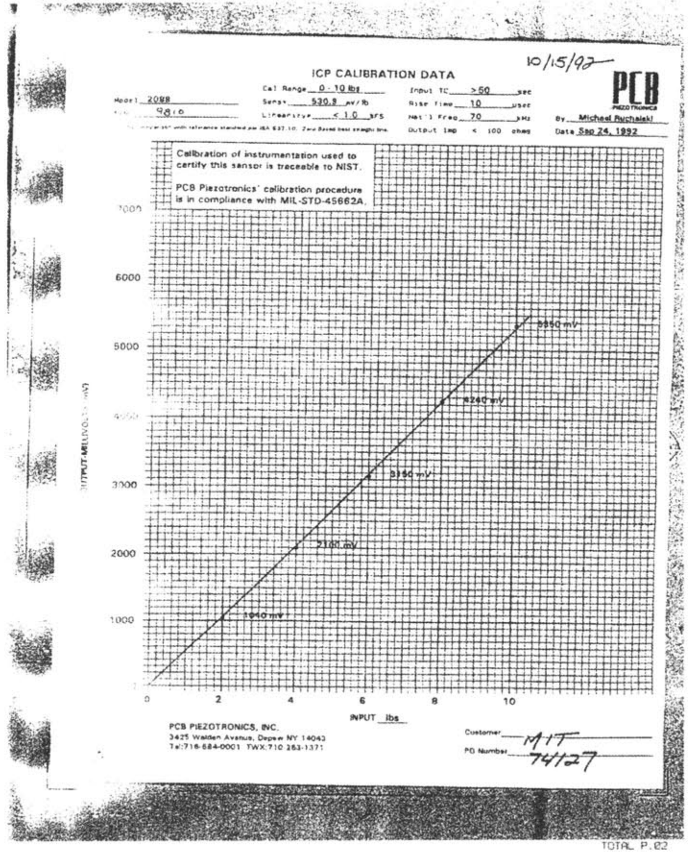


Figure A1. PCB 208B force transducer (right) and specification data.



MAY-14-2001 09:04 PCB PIEZOTRONICS 716 684 0877 P.02/02

10/15/92

ICP CALIBRATION DATA

Model 208B
98 10

Cal Range 0 - 10 lbs
Sens 530.9 mV/lb
Linearity < 1.0 %FS

Input TC >50 sec
Rise Time 10 µsec
Nat'l Freq 70 kHz
Output Imp < 100 ohms

PCB PIEZOTRONICS

By Michael Ruchalski
Date Sep 24, 1992

Calibration of instrumentation used to certify this sensor is traceable to NIST.

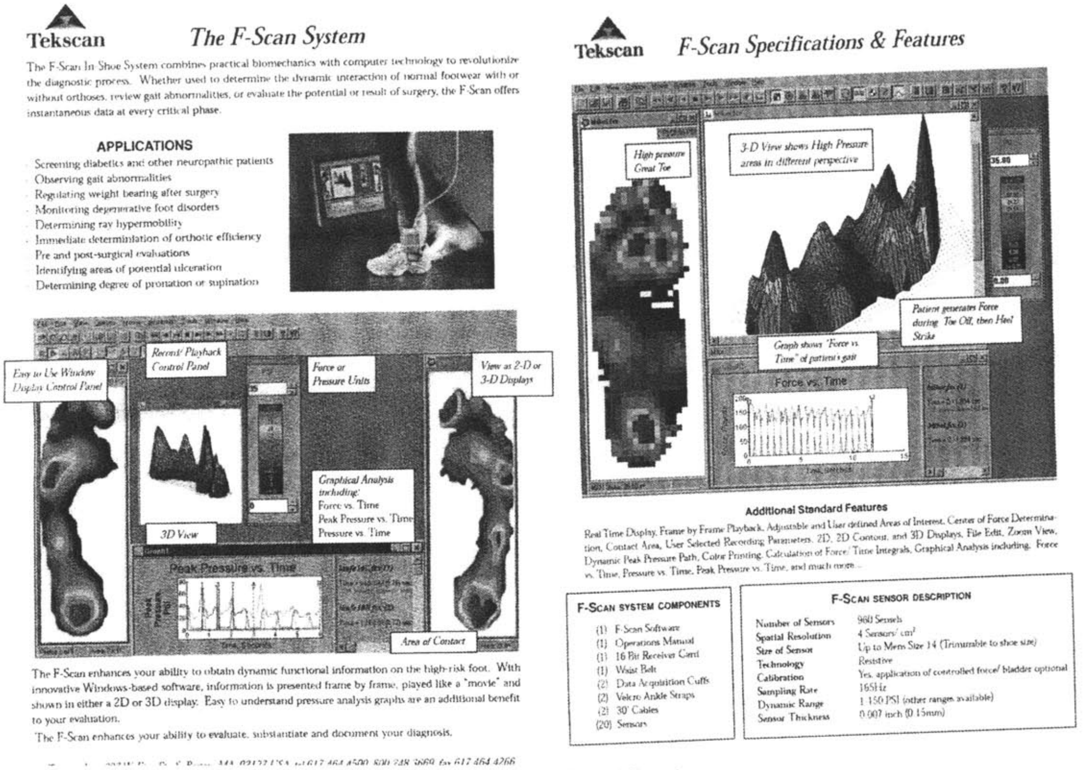
PCB Piezotronics' calibration procedure is in compliance with MIL-STD-45662A.

PCB PIEZOTRONICS, INC.
3425 Walden Avenue, Depew NY 14043
Tel:716-684-0001 TWX:710 263-1371

Customer MIT
PO Number 74127

TOTAL P.02

Figure A2. calibration sheet for 208B (slope = 530 mv/lb).



Tekscan *The F-Scan System*

The F-Scan In-Shoe System combines practical biomechanics with computer technology to revolutionize the diagnostic process. Whether used to determine the dynamic interaction of normal footwear with or without orthoses, review gait abnormalities, or evaluate the potential or result of surgery, the F-Scan offers instantaneous data at every critical phase.

APPLICATIONS

- Screening diabetics and other neuropathic patients
- Observing gait abnormalities
- Regulating weight bearing after surgery
- Monitoring degenerative foot disorders
- Determining ray hypermobility
- Immediate determination of orthotic efficiency
- Pre and post-surgical evaluations
- Identifying areas of potential ulceration
- Determining degree of pronation or supination

The F-Scan enhances your ability to obtain dynamic functional information on the high-risk foot. With innovative Windows-based software, information is presented frame by frame, played like a "movie" and shown in either a 2D or 3D display. Easy to understand pressure analysis graphs are an additional benefit to your evaluation.

The F-Scan enhances your ability to evaluate, substantiate and document your diagnosis.

Tekscan *F-Scan Specifications & Features*

Additional Standard Features

Real Time Display, Frame by Frame Playback, Adjustable and User defined Areas of Interest, Center of Force Determination, Contact Area, User Selected Recording Parameters, 2D, 2D Contour, and 3D Displays, File Edit, Zoom View, Dynamic Peak Pressure Path, Color Printing, Calculation of Force/ Time Integrals, Graphical Analysis including: Force vs. Time, Pressure vs. Time, Peak Pressure vs. Time, and much more...

F-SCAN SYSTEM COMPONENTS

(1) F-Scan Software
(1) Operations Manual
(1) 16 Bit Receiver Card
(1) Waist Belt
(2) Data Acquisition Cuffs
(2) Velcro Ankle Straps
(2) 30' Cables
(20) Sensors

F-SCAN SENSOR DESCRIPTION

Number of Sensors	960 Sensels
Spatial Resolution	4 Sensors/ cm²
Size of Sensor	Up to Mens Size 14 (Trimmable to shoe size)
Technology	Resistive
Calibration	Yes, application of controlled force/ bladder optional
Sampling Rate	165Hz
Dynamic Range	1-150 PSI (other ranges available)
Sensor Thickness	0.007 inch (0.15mm)

Figure A3. Tekscan F-Scan Pressure Sensor Specifications.

Appendix B:

North American College/University Biomechanics and Kinesiology Department Information Resources

At the outset of this project in February 2001, a principal goal was to elicit any information on related research carried out at other institutions of higher learning. To preserve time and resources, it was decided to restrict correspondence to colleges and universities in Canada and the United States, due to the popularity of hockey and football in these countries in comparison to other parts of the world. An e-mail message was drafted stating the intentions of this project and the desire for suggestions and assistance. This message was then sent to every North American college/university biomechanics and kinesiology laboratory discovered within a search period lasting a little over a month.

The results of the exhaustive effort are listed in the following table (Figure B-1, next page). Although no explicit information supporting this particular project was provided by any source, several interested and knowledgeable contacts were established across the continent. These contacts should prove invaluable in the future process of developing a standardized testing method for hockey/football shoulder pads.

List of Colleges/Universities with Biomechanics/Kinesiology Departments*	**Comments**
UNLV (Las Vegas, NV)	Contact: Dr. John A. Mercer. Exp. in impact testing.
Virginia Tech (Blacksburg, VA)	Contact: Dr. Stefan Duma. Exp. in impact loading to bone/joint/tissue.
University of Virginia (Charlottesville, VA)	Contact: Dr. Jeff Crandall. Exp. in impact loading tolerances for bone/cartilage/tissue.
University of Nebraska (Lincoln, NE)	Contact: Nick Stergiou. Exp. in injury force modeling.
Kansas State University (Manhattan, KS)	Contact: Dr. Larry Noble. Exp. in impact testing & shoulder pad evaluation.
University of Manitoba (Winnipeg, MB, Canada)	Contact: Dr. Marion Alexander. Exp. In impact force modeling.
University of Waterloo (Waterloo, Ont., Canada)	Contact: Dr. Stuart McGill & Dr. Pat Bishop (Ret.). Exp. in injury force modeling to tissue/vertebrae.
McMaster University (Hamilton, Ont., Canada)	Contact: Dr. Jim Dowling. Exp. in human joint modeling.
Duke University (Durham, NC)	Contact: Dr. Barry Myers. Exp. in impact injury analysis.
Wayne State University (Detroit, MI)	Contact: Dr. Michele Grimm. Exp. in impact force and musculoskeletal biomechanics in sports.
University of Minnesota (Minneapolis-St.Paul, MN)	Contact: Jack Lewis. Exp. in injury force modeling.
University of Florida (Gainesville, FL)	Contact: Dr. B.J. Fregly & Dr. Jeff Bauer. Exp. in joint modeling and impact testing.
Cal State Northridge (Northridge, CA)	Contact: Dr. Bill Whiting. Exp. in force sensor use.
UC-Irvine (Irvine, CA)	Contact: Dr. Joyce Keyak. Exp. in bone fracture loading.
University of Ottawa (Ottawa, Ont., Canada)	
Arizona State University (Tempe, AZ)	
Ball State University (Muncie, IN)	
Boise State University (Boise, ID)	
Illinois State University (Normal, IL)	
University of Indiana (Bloomington, IN)	
Iowa State University (Ames, IA)	
Michigan State University (East Lansing, MI)	
Cal State Fullerton (Fullerton, CA)	
Montana State University (Bozeman, MT)	
Purdue University (West Lafayette, IN)	
SUNY-Stony Brook (Stony Brook, NY)	
Texas Woman's University (Denton, TX)	
University of Georgia (Athens, GA)	
University of Kentucky (Lexington, KY)	
Stanford University (Palo Alto, CA)	
University of Southern California (Los Angeles, CA)	
University of Calgary (Calgary, Alb., Canada)	
UT-Austin (Austin, TX)	
Texas Tech (Lubbock, TX)	
University of Tennessee (Knoxville, TN)	
Penn State University (State College, PA)	
University of Toledo (Toledo, OH)	
University of Cincinnati (Cincinnati, OH)	
Georgia Tech (Atlanta, GA)	
Southern Illinois (Carbondale, IL)	
UNC-Greensboro (Greensboro, NC)	
UW-La Crosse (La Crosse, WI)	
University of Colorado (Boulder, CO)	
University of Delaware (Newark, DE)	
Virginia Commonwealth University (Richmond, VA)	
University of Vermont (Burlington, VT)	
North Carolina State University (Raleigh, NC)	
Barry University (Miami Shores, FL)	
St. Cloud State University (South St. Cloud, MN)	
University of Illinois-Urbana/Champaign (Champaign, IL)	
Lehigh University (Lehigh, PA)	
UC-Berkeley (Berkeley, CA)	

**List compiled in order of usefulness of contact in future studies, based on reply. Contact established February 2001. Replies received through May 2001.*

Figure B-1. List of biomechanics/kinesiology contacts at North American colleges/universities.

Bibliography

Crandall, Jeff, et al. "Measurement Techniques for Angular Velocity and Acceleration in an Impact Environment." *SAE Transactions, J. Passenger Cars* 1997 v.106 Section 6: 985-91.

Duma, S.M., et al. "Dynamic Injury Tolerances for Long Bones of the Female Upper Extremity." *Journal of Anatomy* 1999 v.194 Part 3: 463-71.

Iversen, Wesley R. "Tactile Sensing, 1990s Style." *Assembly* Feb/Mar 1993: 23-26.

Janda, D.H. "Prevention Has Everything to do With Sports Medicine" (Editorial). *Clinical Journal of Sports Medicine* 1992: 159-60.

King, Albert I. "Fundamentals of Impact Biomechanics: Part I – Biomechanics of the Head, Neck, and Thorax." *Annual Reviews in Biomedical Engineering* 2000: 55-81.

Mann, Roberta, et al. "A New Tool to Measure Pressure Under Burn Garments." *Journal of Burn Care and Rehabilitation* Mar/Apr 1997: 160-63.

Roberts, J. "A Program for Fitting Football Shoulder Pads." *Audible* Winter 1984: 12-14.

Storer, Roberta A., et al, eds. *Annual Book of ASTM Standards.* 72 vols. West Comshocken: American Society for Testing and Materials, 1997.

Viano, D.C. "Mechanism of Fatal Chest Injury by Baseball Impact: Development of an Experimental Model." *Clinical Journal of Sports Medicine* 1992: 166-71.