BIOMECHANICS FROM THE BIG BANG TO THE CLOUD

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The purpose of this paper is to chronicle the development of the field of biomechanics from singularity to present day. It is the Geoffrey Dyson Keynote Lecture for ISBS 2012 in Melbourne, Australia.

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Carl Sagan said "We are made of Star Stuff". Every molecule in our body can be traced to material that initially exploded producing our Universe. The Universe and all of us were born at the moment of this massive explosion called the "Big Bang". This was the moment when a point, the Singularity, followed Einstein's law and converted energy into mass and light.

Billions of years after the Big Bang, our little Solar System was created from the star dust and gravity of an explosion of a Super Nova on the edge of our own Milky Way galaxy. Our Solar System is in a really boring part of the Milky Way Galaxy. We are marooned out here in one of the remote (some may say back water) areas of the Orion-Cygnus Spiral Arm about 20 degrees above the galactic plane and about 28,000 light years from the center of the galaxy. The gravity that created our Galaxy and Solar System is also responsible for the creation of our planet Earth. The gathering of star stuff by gravity produced the place we call Home and continues to rule our lives.

We are the children of these eons of exploding stars. In the heart of a dying star, new elements were made and every single atom in your body has come from these dead stars. The journeys of the atoms that compose us today began at that moment when time and mass and light were born. They have traveled for billions of years through star births and deaths, through light years of space and time. Our Earth, and each of its inhabitants including us, is the result of those explosions. These masses which were created and the gravitational forces are our parents. Now we try to understand and analyze them.

Two scientists, separated by two hundred and fifty years of time and experiences, formulated and explained the laws of nature which relate to our modern field of Biomechanics. The pioneering work and creative concepts of seeing natural phenomena of Isaac Newton and Albert Einstein have provided us with tools to study and understand bodies in motion.

Isaac Newton may or may not have actually sat under an apple tree and watched an apple fall to earth with the moon high overhead. But he pondered the dilemma about falling objects and determined that the same laws that affected the apple falling towards the earth must also affect the moon in its orbit around Earth. Since the objects moved continuously rather than in discreet jumps, he also had to develop a new type of mathematics, calculus, to explain the motions. By applying the same rules to the falling apple from the tree and the rotation of the Earth around the sun, Newton revolutionized the understanding of nature on Earth. The three laws of motion that he developed apply to Mass and Gravity in Newton's world as well as in our own.

Newton's second law of motion, was F=ma and with it, he created our field of Biomechanics. The fact that Force depends on mass and acceleration established the principles that govern any field of Biomechanics.

However, although Newton formulated the laws of Gravity, he really did not understand what Gravity is. Two hundred and fifty years passed before Albert Einstein pondered the question about what Gravity is. By proving that the speed of light is constant and cannot be exceeded, Einstein formulated the Theory of General Relativity which explains the relationship between Mass, Speed, and Energy.

Einstein showed that Gravity is the warping of time and space. There is a theoretical particle, the "gravitron", which is the proposed force carrier although it has not been physically detected at this time. The studies and mathematical enquires into these elementary particles constitute the field of Quantum Mechanics. Of course, Einstein's formulas relate to bodies far away in the Universe, for example with gravitational lensing, as well as the macroscopic World of Quantum theory. Despite the many attempts to develop a "Unified Theory" which will satisfactorily explain the relationship of the most elementary particles and the behaviors of bodies in the vast reaches of Space, the matter is unresolved. However, Einstein's genius demonstrated the relationship of Energy, Mass and Velocity. While we can rely on the relative simple laws of Newton to execute our Biomechanical studies, there may come a day, when we journey outside of Earth's gravitational field such as to Mars or beyond, when we may also need some of Einstein's contributions to the field of motion. In the meantime, we can rely on the Newton's second law.

To the mechanical laws we add the "Bio" or life portion. Once again, we recognize that our existence is due to the Super Nova's exploded "stuff" which was swept into the ball of our Earth. Although much of the first billion years of our planet are unknown, we believe that the processes which created our atmosphere, land, water and life were complex. What we do know today is that the proteins molecules that were created as a result of "Star's Dust" integrated in unique configuration to produce the basic of life we call the DNA molecule with its Chromosomes. This DNA replicates itself to create life and to maintain us throughout our lifetimes.

Billions of years after our Earth was formed, humans appeared and we began our own creative history. One of the greatest of all of our "modern" biomechanicst, was Leonard da Vinci. Leonardo lived from 1452 to 1519 and was one of the first people to study and integrate the "bio" with the "mechanical". He has been called the "Renaissance Man" because of the breathth of his scientific studies, arts, and inventions. His extraordinary genius produced so many inventions and all were developed to integrate human functions with the environment. His designs of contact lens, submarines, war machines, helicopters, and many others surely earn him the title of "biomechanist" if not the first one. Leonardo's attention to the details of humans and their interaction with tools and their environment has transended 600 years and continues to amaze us in 2012.

More than 100 years after Leonardo, another scholar and scientist developed and studied human and machine interactions. Giovanni Alfonso Borelli actually calculated forces on the body at different gaits and positions of movement. Borelli is not as widely known or appreciated as perhaps he should be. What reputation he has is based upon his mechanics, including celestial mechanics, and his physiology. The former, unfortunately, was quickly and completely overshadowed by the work of Isaac Newton. Accordingly historians have undervalued his place in the development of the sciences in the seventeenth century, and they have paid little attention to his career or his personality. He read widely and drew his scientific inspiration from a broad spectrum of the heroes and near-heroes of the early seventeenth century from men such as Galileo Galilei, William Harvey, Johannes Kepler, and Santorio Santorio. He worked on many problems, contributed significantly to all the topics he touched, and in fact played an important part in establishing and extending the new experimental-mathematical philosophy.

In addition to the genius of scientists and scholars of the past such as Leonardo da Vinci, Borelli, and Isaac Newton, the modern world of biomechanics depends to a great extent on the development of photographic developments. Much of this early work occurred during the first decades of the nineteenth century.

Joseph Niépce, Louis Daguerre, and William Henry Fox Talbot are three major inventors who worked to develop the techniques of photography. Niépce and Daguerre eventually became partners in France and worked to refine the techniques of photography that are the predecessors of modern instant photography. Talbot, an Englishman who was unaware of the work of Niépce and Daguerre, discovered a method of photography that enabled the making of multiple prints through the use of a negative. It is Talbot's technique that is most akin to the photography process that is used in the modern film industry.

In 1890, a French scientist, Jules Marey, studied the movement of animals using static photographs which were recorded in succession. His revolutionary idea was to record several phases of movement on one photographic surface. In 1890 he published a substantial volume entitled *Le Vol des Oiseaux* (*The Flight of Birds*) which was richly illustrated with photographs, drawings, and diagrams. He also created stunningly precise sculptures of various flying birds.

Marey's photographic skills contributed to the high speed photography we employ today. In 1882, Étienne-Jules Marey became the first person to eliminate the need for multiple cameras. The French inventor did this by capturing motion with a photographic gun that initially used a glass plate that rotated like a gun barrel to capture the pictures.

While others subsequently developed similar primitive camera techniques to photograph motion, it was the American inventor Thomas Edison, with the help of his assistant William Dickson, who ultimately developed the basic film camera system that would become the standard equipment of the film industry. After seeing Marey's invention, Edison became convinced that the ultimate solution required a flexible film stock. He asked George Eastman, an early leader in the creation of photographic products, to develop such a film. Eastman successfully produced the flexible stock, patented in 1884, according to Edison's specifications. The film was thirty-five millimeters wide and had two rows of perforations, four holes per frame that ran the length of the film. By 1892, Dickson had developed a fully efficient camera, the Kinetograph that used sprockets to advance fifty-foot lengths of this film stock through the camera to capture films that lasted less than thirty seconds.

Following the development of some of the photographic work, one of the first representation of human movement at Gait Analysis were Brune and Fischer. Braune was inspired by the photographic work of French scientist Étienne-Jules Marey (1830–1904) regarding anatomical movement. Marey believed that movement was the most important of all human functions, which he described graphically for biological research in *Du Mouvement Dans Les Functiorls Da La Vie* (1892) and *Le Mouvement* (1894). This led the way for Braune's experimental and anatomical studies of the human gait. These studies were published in the book *Der Gang des Menschen*.

The study of the biomechanics of gait covered two strides of free walking and one stride of walking with a load. The methodology of gait analysis used by Braune is essentially the same used today. For the first time, "stick figures" were used to illustrate a human Gait.

Brauno and Fischer were the first one to formulate how to extract three dimentional measurement from photographs. This method of calculating image coordinates was revolutionary at the time. However, their ideas are used today as the bases of the Direct Linear Transformation employed in 3D analysis.

Another major contribution to modern biomechanics was developed by Eadweard Muybridge, a British-born photographer. Muybridge was a brilliant and eccentric photographer who gained worldwide fame photographing animal and human movement imperceptible to the human eye. He was hired by railroad baron Leland Stanford, in 1872, to settle a bet that Stanford had made with a fellow horseman regarding a horse's gallop. The bet was whether the horse had all feet in the air at some point during the gallop or not. Muybridge used photography to prove that there was a moment in a horse's gallop when all four hooves were off the ground at once.

Thus, Muybridge created the first "motion picture" by using a series of twenty-four cameras set at one-foot intervals to photograph a horse as it galloped along a racetrack. As the horse passed each camera, its hooves tripped threads that were attached to each of the cameras, thereby creating a series of twenty-four images that showed a horse in motion. *Freeze Frame* explores the famous photographs of animal and human locomotion that Muybridge made at the University of Pennsylvania between 1884 and 1887. For 100 years, historians considered these photographs to be scientific studies of the body in motion.

All of these scientists, inventors, photographers, and the various technological developments bring us to the great sports scientist, Geoffrey Dyson. Dyson had a lengthy and powerful academic and coaching career. He was the coach of the British Olympic Teams in 1952, 1956, and 1960. In 1962, he first published his book on the Mechanics of Athletics. He was a speaker for the International Olympic Academy and conducted athletic courses in 14 countries. Dyson revolutionized sports sciences by introducing physics to the analysis of sports

The International Society of Biomechanics for Sports was started based on Dyson's personality and knowledge. It was Dr. Juris Tserauds who was inspired by Dyson to start the ISBS organization in the 70's. From those early days, the organization has grown and produced wonderful scientists each of who honors and pays tribute to Geoffrey Dyson through their own contributions to science. I am amazed and privileged to be a Keynote speaker in the ISBS conference here in Melbourne Australia and to receive the Dyson Award. I read that the Geoffrey Dyson Award and Keynote Presentation is the most prestigious award offered by ISBS and that it is awarded to an individual who through his/her professional career has embodied and carried out the mission of ISBS.

The mission of ISBS is:

To encourage excellence in the study of biomechanics related to coaching, Geoffrey Dyson and his book: The Mechanics of Athletics *teaching, training and performance of sport and exercise.*

I appreciate the honor and recognition that I receive by this award. I hope that I can inspire other students and scientists to follow in the same footsteps that I did by reading and studying Geoffrey Dyson. My presentation today is in honor of Geoffrey Dyson who I had the privilege to meet several times. His personal influence and presentations guided and inspired me to devote my life to the field of "The Mechanics of Athletics". I was an Olympic participant in Rome (1960) and in Tokyo (1964) as well as a student at the Wingate Institute in Israel. During these years, I studied Dyson's book, "The Mechanics of Athletics" until it was nearly worn out! His explanation of sports events helped me to understand that if your psychology is perfect and your physics is wrong, you will be a happy loser. To succeed in sports, your physics must be correct.

When I registered for my Master's degree at the University of Massachusetts, my focus was to pursue studies in Biomechanics. My first biomechanics professor was Dr. James who used the Dyson book as the class text book. In 1968, the Olympics were held in Mexico City. As a former Olympian and a student of biomechanical studies, I decided to travel to Mexico City with the Kodak Cine Special spring loaded camera which could take 64 frames per second. At that time, the Kodak Cine camera was the fastest available for recording on regular 16 mm. film. I hoped that I would be able to calculate the physical parameters that Dyson represented in his book by securing film from these Games.

Prior to the 1968 Olympics, I had attended some conferences related to coaching in Track and Field events. I had met the president of the International Track and Field Association, Mr. George Dales, at these conferences. Coach Dales was able to arrange entrance tickets to the main track and field venue for me in Mexico City. Once on the field, I set my one camera on a tripod and began filming any event in which athletes were competing. At that time, security was not an issue and with my credentials I could go to any place on the field as long as I did not interfere with the event. I was the only one walking with my camera and tripod and could film any event at high speed. The subsequent studies represent the first Biomechanical analyses to be performed on Olympic Sports based on films made of the actual performances.I was standing beside the long jump pit to film of two famous jumpers, Ralph Boston from the USA and Ter Ovanesyan from Russia. They were both former World record holders who had competed with each other for years. Preparing for his jump was an unknown jumper. I decided to film his jump as preparation of the others. The jumper raced down the runway, launched himself into the air, and broke the World Record. The jumper was Bob Beamon and his jump broke the previous World Record by two feet.

To analyze Bob Beamon's jump, I had to use a film projector which projected the image onto a mat glass to which I taped some special tracing paper. It was a laborious task since the tracer was always blocking the projected image. It was a dance of sorts to mark a point, move out of the way, check, and correct the mark when necessary. However, in spite of all of these difficulties, this was the first time biomechanics of sports was applied for an international competition. The ISBS organization did not exist yetTo process the results, I had to write a computer programs to calculate the coordinates and derive displacement, velocities, and accelerations. I used the FORTRAN language on the Control Data University main frame computer. Main frame computers at that time were in the nine to ten million dollar range. How much things have changed since then!

In the early 1970s, there was a new professor at the University of Massachusetts in Biomechanics. His name was Dr. Stanley Plagenhofe and he was a pioneer in applying computer programs to analyze human movement. His contributions to biomechanics have gone largely unsung perhaps because of his difficult personality. However, he had some excellent quantitative concepts and computer applications which ultimately contributed to the growth of our biomechanical community in analyzing sports.

One of Dr. Plagenhoef's contributions was an elaborate configuration for tracing the film. Unfortunately, the process for the biomechanical analysis remained excessively tedious but, at least, the tracer did not continuously block the image. The process required projecting 16mm film one individual frame at a time. The film sequence was projected through a series of angled mirrors onto a glass-topped table. As each frame appeared, the location of the body's joints was "traced" by marking points on a large piece of paper which had been taped onto the glass top in a process known as "digitizing". The next step required measuring the various angles and distances, carefully recording them in a table. Then one sat for hours at the computer center to punch the numbers onto computer cards. These computer punched cards were then submitted to the computer center for processing by the biomechanical program. Then the processing time usually required an additional day.

The kinematic parameters which the program produced were the positions, velocities and accelerations of each of the selected joints. The information for any one of these joints and for any of the selected kinematic parameters could be plotted on paper. The plotted data yielded diagrams such as the following examples of stepping from a table, jumping into the air, and hitting a tennis serve.

Some of the earlier analyses of sports biomechanics were executed in the late 1960's. One of the analysis was of the Russian Lusis who held the World Record Holder in the Javelin. The body diagram with the point identified and a velocity curve for the joints are shown. For the first time, Olympic performances were analyzed and published for the coaches and athletes. Velocities curves yielded link sequences of World Record Performance. The publications of the results were quickly studied by many coaches especially those in what was, at that time, the Soviet block. Many other coaches were able to read and study biomechanical results published by Coach George Dales in the International Track and Field Coaches Quarterly Journal. After the ISBS was established, many quality presentations were available through this organization.

Biomechanical analysis was a fantastic tool for quantifying sports performances despite the drawback that it was a slow tedious process. However, I continued to search for a solution to the slow and tedious procedures. There should be some way to get the image coordinates directly into the computer more quickly than by tracing films and punching cards. There were no personal computers at that time so everything had to be transmitted to the main frame multi-million dollar computer.

At the Dartmouth College Medical School, I saw a researcher using a device to outline a brain tumor from an X-ray. I wondered if the device could be modified for my uses. I wanted a pen that could touch each joint center on a recorded film sequence, a sound would be emitted by the pen, and the sound would be transmitted and used to determine the x and y coordinates for each joint center for each frame of the film.

I had an idea that the bottom and side of a digitizing area frame would have built-in microphones. A "pen" would create a sound that would be detected by the microphones. The pen would create a spark with a certain frequency which would propagate the instant that the glass surface was touched. The first microphone that detected the arrival of the sound would be the one located at the shortest distance from the pen in both the horizontal and vertical directions. These perpendicular microphone locations represented the x and y coordinates. The equipment would transmit the x and y values to be punched onto a paper tape on the teletype. After the film processing was completed, the paper tape could be submitted manually to the computer. An acoustic coupler could also be connected so that the data could be sent directly to the computer. In this fashion, there would be a direct computer connection with a backup paper punched tape. After the x and y coordinate data was saved in a computer file, the biomechanical analysis program could be executed.

Thus, by inventing the "Sonar Digitizer," I had developed a unique device which would rapidly decrease the time and reduce the effort which accompanied the digitizing process. Rapid identification and stored information of the body's joint locations would greatly enhance the biomechanical quantification process.

I met the manufacturer who manufactured the equipment used at the Darmouth Medical School to outline the tumors. The company constructed a device according to the specifications which I gave to them for the sound and microphone arrangement. Thus, the "Sonar Digitizer" was built for me and was installed in the Laboratory in my Kitchen. One of our first project which used this device was for the Universal Gym Equipment Company.

Biomechanical instrumentation, programming, and visual tools improved throughout the years. Movie grade film was replaced by video and cameras became smaller and faster. Some of the original projects were collected at film rates of 10,000 frames per second but these required enormous expenses. Newer, video cameras are sufficiently fast with variable shutter capabilities so that it is currently possible to own many cameras for less than what it had cost to rent the high speed cameras of the past. Computers have become smaller and extremely fast as they progressed from expensive, bulky main frames to mini computers and, finally, to personal computers. In addition to the video and cinematography data acquisition improvements, force plates and EMG can be incorporated to further enhance the quantification and understanding of movement.

For example, in 1975, mini computers became practical, available, and affordable. I purchased one of the first Data General computers, the Nova-3. Unfortunately, as with every computer change, it was necessary to convert all of the biomechanical programs to function on the new operating system of the Nova-3. In 1977, Sports Illustrated published an article on the state of the art of analyzing athletes utilizing Biomechanics. This seven-page article in Sports Illustrated showcased biomechanics to the whole world. It opened many avenues for all biomechanists in their efforts to understand movement.

In the early 1980's, "Desk Top" computers arrived with the introduction of the Apple and IBM Personal Computers. Once again, biomechanical programs were converted to run on these computers. Equally important as the hardware associated with collection of data is the software which runs the analysis. One of the most significant modern contributions to biomechanical analysis was the ability to quantify movement using three orthogonal views. There were many contributors to the 3D analysis of athletic performance. Among many developers of software who I consider as great contributors were Herbert Hatze and Herbert Woltring. They were the main contributors to all Three Dimentional Analysis of Sports activities.

Another great leap forward occurred in the early 1990's with the introduction of the Internet. The Internet provides access to a worldwide collection of information resources and services as a window on the ever-expanding world of on-line information. The new communication links afforded by rapid satellite/computer exchanges enabled the field of Biomechanics to advance into a new age of technology, resources, research, data base development, as well as interaction among scientists.

Utilizing the tools available in Cyberspace, a biomechanist can retrieve and display data as well as documents from virtually anywhere on the planet. Studies can be conducted at multiple locations and data rapidly exchanged among these sites. Thus, with the Internet's hypermedia-based interface, documents can include color images, text, sounds, and animation. As a hypermedia technology designed for searching and retrieving, the Internet provides a unified interface to the diverse protocols, data formats, and information archives appropriate for biomechanical endeavors. Using electronic links, known as Hyperlinks, specified information can be incorporate within a document by embedding full-color images, sounds, graphs, bibliographies, supplementary resources, and data bases located within that text or at some distant site. This interface allows information located around the world to be interconnected in an environment that permits users to access the information super-highway by clicking on "hyperlinks". Similarly, complex biomechanical research segments at different research sites can be "tethered" through these "hyperlink" phases. Biomechanical research and subsequent reports become virtually three-dimensional with this multiple level access.

One of the first sports study to use the Internet was performed in the 1996 Atlanta Olympics. Data was collected on the field and transmitted to a number of Universities for processing the data and within 24 hours, the results were returned for use in a conference with track and field coaches from around the World. Dr. Al Finch was a major contributor to these biomechanical studies.

At the 2004 Athens Olympics, the internet played an integral part in the Shot put event. Data was recorded on video cameras, captured into the computer, and transmitted to universities for biomechanical processing. Within a short time, the coaches were presented the results.

Thus, biomechanics studies of Sports have contributed to the quantification and understand of many Olympics events. The results are shared with coaches and many have been presented at ISBS conferences throughout the years.

Part of the future of biomechanics, of course, is in the “Cloud”. This concept allows applications to run from technology where high speed videos will reside in a global database. Digitizing and filtering programs as well as display will run “on line” from the Cloud. A biomechanical study can be conducted with two people capturing film with their smart phones, exchanging data, digitizing on the phone’s screen, processing the data, and uploading the results to the “Cloud” for all to share.

The next logical phase of computerized biomechanical analysis is to make it available in the "cloud". In that way, biomechanical analysis can be viewed as a service rather than a product.

This will have significant advantages for the end user, because many different types of resources can be pooled together and be made available for a much more complete analysis than previously thought possible.

These types of resources include computing resources for performing whichever numerical analysis necessary for the problem at hand, storage resources for keeping a database of virtually unlimited size, and bandwidth resources for making the information available whenever and wherever desired. Resources not only include computing resources, but also human resources such as experts performing the analysis itself or yet others drawing conclusions and making recommendations. The cloud is the facilitator to present a coherent picture of all information of interest.

Not only biomechanists, but any user with a network connection will have access to this sophisticated system. Therefore the system must support many different types of users, such as experts, trainers, coaches, students, children, and of course the athletes themselves. Each type of user can have the information presented according to his or her level of knowledge or interest, and the information presented can be accompanied by all kinds of training and tutorial materials within the context of the analysis itself. The cloud is the system that makes this possible.

Users will no longer require dedicated computers for performing analyses, but rather the information can be collected, viewed and analyzed from any device connected to the network, whether they are computer workstations, internet terminals, tablets, smartphones, laptops or other. All an end user needs for injecting new data into the cloud is a data collection device, whether it is a phone, a tablet, or something more sophistated, and a network connection to upload this information to the cloud. Once the information is there, it can be analyzed and viewed on any device connected to the network.

The information stored in the cloud can be combined and be made available in many different ways. Any performance could be compared with any other, for example to evaluate the consequence of applying a different technique, or to objectively measure the improvement of a training program, or to compare techniques between different athletes, or... well, the sky is the limit.