Project Description (Principal Investigator: Hugh Ching, October 1, 2011)
Title: Jumpulse and Law of Touch Demonstrated by Prolonged Contact between Ball and Racket during Collision

I. Introduction, Objectives, and Significance

This research proposal deals with the effect of a force applied during collision. It relates to the solution of touch, which can be defined as collision without bounce. The research addresses two intriguing problems, which could have immediate world-wide and historical interest. The first problem is the internationally controversial problem of prolonged contact in sports, particularly, in tennis. The second problem deals with two missing concepts in the description of motion: jumpulse and the Law of Touch, both of which are needed in the solution of touch, which can be defined as permanently prolonged contact at low speed, while prolonged contact is at high speed.

This research claims that prolonged contact can be achieved by applying during collision a precisely timed jumpulse, which is defined as a sudden change of force, as impulse is a sudden change of momentum, where force is the time derivative of momentum. The applied force, jumpulse, is a step function of force vs. time and requires that acceleration be changed by a finite amount instantaneously. This proposal will challenge and search for people world-wide, who can think *physically* how to keep a racket in prolonged contact with a ball. Up to now only four people, Ta-You Wu, T. L. Kunii, Rustin Roy, and PI, can. The problem of prolonged contact, which has evaded all the physicists since Newton, will challenge the thinking ability of scientists.

The historical relevant second problem involves the Law of Touch, which states that acceleration, unlike position and velocity, can change instantaneously by a finite amount, and which is needed to achieve prolonged contact. Because both position and velocity need time to change, the Law of Touch is not obvious. Neither jumpulse nor the Law of Touch are recognized in the laws and forces of nature from Newton to Einstein to super string theory, where, in terms of the current physics, the spring and other forces in this research mostly have electromagnetic origin [Ref. 1].

Does prolonged contact exist? And, if it does exist, how can one achieve it? These are the two main questions to be answered or goals to be achieved in this research both experimentally and theoretically. The usual contact time in a collision between a tennis ball and a racket is about 4 milliseconds. To detect the interaction visually and to convince both the sports and the physics community world-wide of the definite existence of prolonged contact, a slow motion video camera with the speed of 7000 frames per second or better will be needed. All the school children from K12 to college and graduate school, and probably all the tennis players around the world, will be excited by the result of this research, if it can show that prolonged contact does exist and can be taught. Also, the introduction of the Law of Touch, which enables humans, and eventually robots, to touch could have historical significance both theoretically and practically.

Can acceleration or force be increased instantaneously by a finite amount? In classical mechanics, position cannot be changed instantaneously. For an object to move from one position to a different position, it must occur with finite, not zero, time. Velocity cannot be increased instantaneously. For example, it takes a car to go from 0 to 60 miles per hour in about 3 seconds (fastest today). But, can acceleration change instantaneously? Both touch and prolonged contact depend on the possibility of changing acceleration or force instantaneously by a finite amount.

When a racket hits a ball, the positions of the racket and the ball are the same during impact, where the velocity of the ball changes from negative to zero and then to positive, and the acceleration also changes from zero to maximum to zero. Sometime during the impact, the velocities of the ball and the racket become the same. In order to have two objects moving together, they need to have the same position, the same velocity, and the same acceleration (for simplicity other derivatives are neglected). Two possible strategies in achieving prolonged contact have been proposed in an international debate initiated by this proposed research. The first strategy is to increase the velocity of the racket with acceleration in order to catch up with the velocity of the ball. The second strategy, which is proposed in this research, is to increase the acceleration instantaneously at a precise moment when the ball and the racket have the same velocity. To increase acceleration instantaneously requires the newly formulated Law of Touch.

The Law of Touch states that acceleration, unlike position and velocity, can change by a finite amount instantaneously. Graphically, the sudden increase in acceleration is a step function of acceleration vs. time, as jumpulse, a word coined by the Father of Chinese Physics Ta-You Wu [Ref. 2] is a step function of force vs. time. The Law of Touch leads a more general law, which states that any time derivative of position higher than the velocity can be changed by a finite amount instantaneously. Jumpulse is measured in **w**eight **u**nits, where one wu equals one newton.

Touch is closely related to prolonged contact in that when a robot finger tries to touch a surface, it bounces off, as a ball bounces off a racket. According to T. L. Kunii, Japanese Sixth Generation Computer Science, Robotics, failed because robots cannot touch. This proposed research chooses to study prolonged contact rather than touch because the problem of touch could be trivialized for being a common daily affair, and everyone can do it easily, but prolonged contact seems to be achievable only by a handful of the most gifted athletes in history. If prolonged contact is made possible with jumpulse applied at a precise moment and the Law of Touch, it will support the extraordinary claim that the nature of an applied force is most often a step function of force.

As shown in **Table I**, the concept of jumpulse is an extension of the concept of impulse and is in the system of impulse and jumpulse, not in the system of velocity, acceleration, and jerk or of momentum, force, and yank. Both impulse and jumpulse can be derived from force and jerk, but both concepts should have their own places among the fundamental concepts in physics, because of their significance, particularly, jumpulse, which is useful in describing the extremely important phenomenon of touch or collision without bounce.

Table I Terminology of Motion [Ref. 3]

Velocity	**Acceleration**	**Jerk** (ISO) **Jolt**(?)	**Snap** (?)	**Crack** (?)	**Pop** (?)
Momentum	**Force**	**Yank** (?)	**Tug** (?)	**Snatch** (?)	**Shake** (?)
Energy (Lagrange: Mass x Velocity Squared)	**Energy of Acceleration** (Appell:Mass xAcceleration Squared)	**Energy of Jerk** (?)			
Impulse (Sharply Sloped Function of Momentum vs. Time)	**Jumpulse** (Step Function of Force vs. Time) Proposed: **?**	**Kumpulse** (?)	**Mumpulse** (?)	**Numpulse** (?)	**Ompulse** (?)

[NOTE: (?) denotes items not recommended to be named before their significant applications.]

The introduction of the new concept of jumpulse is justified by its many possible applications. Jumpulse is achievable and can be used to explain any phenomena involving the release of a force, such as that of a compressed spring. The many demonstrations of the concept of jumpulse are (1) Touch, (2) Prolonged contact in sports, (3) Debounce switches, (4) Active car bounceless shock absorbers, (5) Stick-slip, (6) Bang-bang control, (7) Spacecraft docking, (8) Spring or air rifles, (9) Impedance control, (10) Mechanics of martial art, (11) Tension Integrity and biotensegrity icosahedrons, (12) Mouse trap, (13) Medieval Siege Weapon (catapult), (14) Earthquake, (15) Others, among which touch and prolonged contact are the most significant.

Jumpulse and impulse are closely related. Jumpulse can be described as a sudden change of force. Impulse is a sudden change of momentum. Force is the time derivative of momentum. Thus, Jumpulse ranks one derivative higher than impulse. However, there is one fundamental conceptual difference between jumpulse and impulse. This difference is the Law of Touch, which will be experimentally verified in this research. In practice, an instantaneous change of force is usually created by the instantaneous removal of one of one or more existing forces. Here, the similarity of removing a velocity does not apply, and even in a collision, the change in velocity is accomplished by a spring force acting on the object for a small, but still finite, time.

A contradictory comment made by a researcher of stick-slip and bang-bang control can be used to validate the relevance and the need of the Law of Touch and to elucidate the difference in the two strategies on how to achieve prolonged contact (The comment is in quotes):
"A collision without jumpulse results in two outcome velocities. A timed ideal delta-function impulsive force applied on one body (say the racquet) should (ideally) instantaneously change the velocity, conceivably to match the outcome velocity of the ball, to maintain the prolonged touch that is sought." The phrase "…instantaneously change the velocity, conceivably to match the outcome velocity of the ball…" is in direct contradiction to the Law of Touch, which says only acceleration can be changed instantaneously. The short interval of two similar velocities offers a window of opportunity to increase the acceleration, which is possible through the Law of Touch.

If the sudden change of acceleration is what enables prolonged contact, the result will not only support the Law of Touch, but also explains why mechanical designs depending on the sudden change of velocity, such as robot touch, stick-slip and bang-bang control, impedance control, and non-accelerating follow-through tennis stroke, have, thus far, failed in avoiding bounces. The preliminary study of the first strategy, which tries to increase of velocity of the racket to catch up with the ball, shows that the increase of the racket velocity will generally increases the relative velocity of the ball and the racket. The general problem of force applied during collision is difficult to think physically. A good thinker will extract the essential features of the interaction.

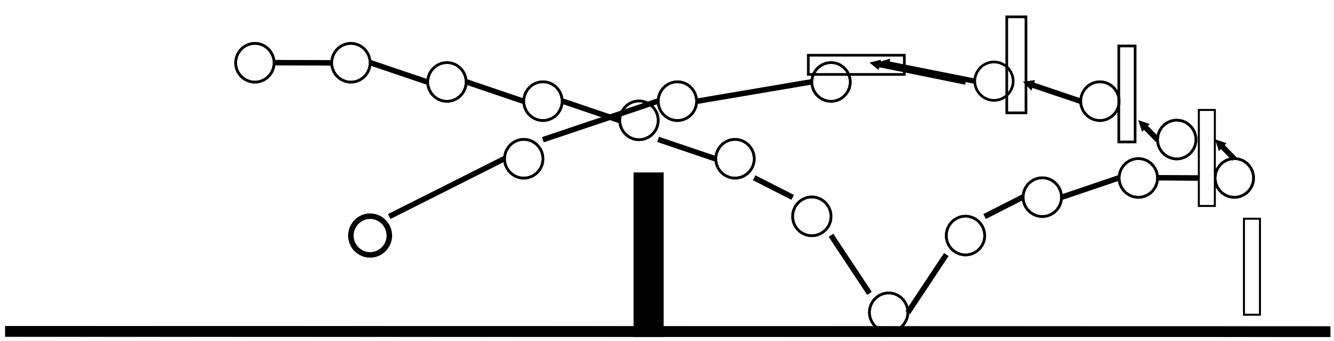
Jumpulse is far more relevant than impulse because a precisely timed jumpulse is the solution of touch. Furthermore, when one moves one's hand from rest, one is most likely applying a jumpulse, which is more efficient than a force. It can also be speculated that most changes of velocity are initiated by a finite, rather than a gradually changing force from zero. The instantaneously applied finite force is a jumpulse. The term and the application of jumpulse could become as popular as force, for it is omnipresent in areas, which are currently explained vaguely by force. Even more significant than being the fundamental mechanical concept in producing a motion, jumpulse will be the central theme in building robots, which can safely come into contact with an uncontrolled environment and, thus, can replace all physical labors. Jumpulse is a concept significant enough to stand by itself because it could be the most commonly observed form of an applied force; it describes how motion starts better than force.

What is the secret of consistency in sports? The secret is ball control. When a player can carry a ball on his racket, the player can guide the ball to the desired direction, add speed or spin to the ball, and, in general, control the subsequent motion of the ball. Thus, the secret of consistency is the ability of a player to keep a ball on the player's racket for a prolonged period of time.

There is by now sufficient historical evidence that there is a common trait among athletes who dominate their respective sports. This trait inevitably involves ball control or the ability of a player to keep the ball on the racket for a prolonged distance or time, in addition to the player's athletic ability. In the past, several professional athletes dominated their sports with their consistency. Jack Nicklaus has said: "I swear that I can carry the golf ball on my club." Similarly, Ted Williams has commented once that he does not hit the baseball, but whips it out. In table tennis, China's Chuang Tse-Tung, who has dominated table tennis in the 1960s, and Taiwan's Chen Yin-Lieh, who is the inventor of the loop, can carry the ball on his racket for up to a foot. Roger Federer, who currently dominates tennis, has a forehand, which, all the tennis fans around the world can witness on TV, carries the ball on his racket for a seemingly extraordinarily long time. From these actual historical records, it is probably safe to say that prolonged contact, the secret of consistency, could be the most important phenomenon in sports.

Jumpulse is the solution of touch or collision without bounce and, when applied with precise timing, can prolong the contact. Understanding the exact mechanism of prolonged contact can extend the natural human ability of touch from the hand to the racket. Historically, the number of players, who can do prolonged contact without training, is very small indicating further that the prolonged contact is not a trivial ability, mastered only by very few exceptional athletes without the knowledge, but with exceptional nervous systems. Prolonged contact is shown in **Figure 1**.

Figure 1 Prolonged Contact



From the point of view of jumpulse, physical education is more difficult than physics. Most physics problems involve about five variables, but the problem of prolonged contact requires one to deal with around twenty-five variables (5x5), namely, the interaction of five variables with five variables (mass, velocity, acceleration, spring constant, and time) from the two ends of a spring.

The discovery of prolonged contact is related to the change of the international regulation in tennis regarding double hitting [Ref. 4, 5], which has been predicted by the Principal Investigator to be a necessary consequence of ball control. Not realizing double hitting, most other sports rules are violating physics. The violation of physics in sports rules regarding double-hitting is another evidence of the lack of understanding of the phenomenon of prolonged contact. This research will settle once and for all whether double-hitting should or should not be allowed.

In conclusion, jumpulse is a sudden change of force. When applied with precise timing, namely, at the moment of impact, jumpulse allows prolonged contact between the ball and the racket. When the ball is in contact with the racket, a player of tennis, table tennis, golf, baseball, etc. can hit it in the desired direction, add power or spin to the ball, etc. Jumpulse is also the solution of touch. Prolonged contact conceptually is simply an extension of touch, from the hand to the racket, the club, or the bat. Nature has given human beings the ability of touch, while no robot today can touch, and this research will extend the human natural ability of touch to the sports motion of prolonged contact, which, except for very few, needs special knowledge and training.

II. Technical Description of Problem of Touch and Prolonged Contact

What Is Jumpulse?

Jumpulse is a sudden change of force. Newtonian impulse is a sudden change of momentum. Force is the time derivative of momentum. Ta-You Wu coined the word jumpulse. However, jumpulse is fundamentally different from impulse, which still involves finite time. This proposal is based on the speculation that force can change or be changed instantaneously, but momentum cannot. In other words, acceleration, unlike position or velocity, can change by a finite amount instantaneously. This physical phenomenon is referred to, for convenience, as the Law of Touch, which could be one of the most relevant additions to Newton's Laws of Mechanics, because it pertains to touch, or collision without bounce, one of the most common phenomena in nature.

In order to prove the Law of Touch, one can ask oneself: "What is the acceleration of a ball as soon as it is released from the hand to a free fall?" The answer should be g, the gravitational acceleration. Similarly, when a compressed spring is release, the object in contact with the spring instantaneously experiences the expansion force of the spring proportional to the compression.

To get a physical understanding of jumpulse, one can visualize the interaction between a bowling ball and a spring mattress. If one drops the bowling ball on the mattress, the ball will push down the mattress to a maximum indentation, where the velocity is zero, and after which the ball will bounce up. If one presses a finger on the bowling ball at the moment of maximum indentation to stop the ball from rebounding, the sudden force applied/experienced by the finger is a jumpulse. Ta-You Wu's formal definition of jumpulse [Ref. 2] is related to the Green's and delta functions:

$$\{ (\mathbf{J}_i, \mathbf{t}_i) \mid \mathbf{J} \equiv \int_{\mathbf{t}_i} \mathbf{m}\, (\mathbf{d}^3\mathbf{x}/\mathbf{dt}^3)\, \mathbf{dt} \ \ \text{with } \mathbf{m}(\mathbf{d}^3\mathbf{x}/\mathbf{dt}^3) \geq 0 \ \ (\text{or } \mathbf{m}(\mathbf{d}^3\mathbf{x}/\mathbf{dt}^3) \leq 0) \text{ in the entire interval } \mathbf{t}_i \}$$

This definition is now of historical significance, pointing out a crucial missing concept in applied forces, which have been generally neglected by Newtonian Mechanics and in the study of the mostly passive forces of nature by Newton. The nature of jumpulse is described by PI as:

$$\mathbf{J} \equiv \int_{\mathbf{t}_1}^{\mathbf{t}_2} \mathbf{m}\, \mathbf{d}^3\mathbf{x}/\mathbf{dt}^3\, \mathbf{dt}, \quad \text{where } (\mathbf{t}_2 - \mathbf{t}_1) \text{ approaches and can equal zero}$$

which implies that acceleration, unlike position and velocity, can change instantaneously. In the above definition, $\mathbf{d^2x/dt^2}$ is a step function, with infinite $\mathbf{d^3x/dt^3}$ being easily achievable. As Newton treated impulse, difference equations would be a better way to treat jumpulse,

Precise Timing

Generally, two objects or particles move together if they have the same position, the same velocity, and the same acceleration, plus all the same higher-order derivatives of time. This is also the definition of a fluid, as described in the Generalized Fluid Description [Ref. 6]:

$$\frac{Df}{Dt} \equiv \frac{\partial f}{\partial t} + \dot{x}\frac{\partial f}{\partial x} + \ddot{x}\frac{\partial f}{\partial \dot{x}} + \dddot{x}\frac{\partial f}{\partial \ddot{x}} + \ldots + x^{(\text{n dots})}\frac{\partial f}{\partial x(\text{n}-1\text{ dots})} + \ldots + \infty$$

When the ball is in contact with the racket, they have the same position. The next condition to be satisfied is that they have the same velocity. When the ball and the racket surface are moving with the same velocity, the ball experiences an outward force accelerating the ball out the racket. To keep the ball in contact with the racket, a force equal to the spring force must be suddenly applied at the precise moment when the ball and the racket have the same position and the same velocity. This instantaneous change of an applied force is called jumpulse, which, in term of the time scale, is a delta function within a delta function of the impulse to achieve prolonged contact.

"Seeing" the Ball with the Mind

The normal human reaction time from the eyes to the hand is about 50 milliseconds, while the interaction time of the ball with the racket is about 4 milliseconds. There is an over an order of magnitude difference between the two times; to reacting to an impacting ball is impossible.

However, the way that a player times the hitting does not only depend on the eyes and hand coordination; the incoming ball is also "seen" with the mind. A player visualizes the incoming ball in the mind and the hand reacts to the hitting according, too, to the visualization in the mind. In fact, the hand reacts to all the senses, mostly to the eyes, the sound, the feel, and the mind.

Physics of Double Hitting

"Double Hitting" plays a central role in the training of Jumpulse Tennis, Table Tennis, and Golf. Also, it is a direct consequence of acceleration. The possibility of double hitting always exists when a player accelerates the racket or the club. Double hitting is considered illegal in most sports regulations. According to physics, unless acceleration is outlawed, double hitting in one smooth stroke should be considered legal. Because of its importance, the physics of double hitting is presented here. Double hitting is also useful in the training of prolonged contact.

Double hitting is just a laymen's term for multiple bounces, but is also used for clarity as a legal term in sports. Generally, when a ball hits a racket with constant velocity, it would just bounce off with one bounce. The ball oscillates in and out of the racket in a half cycle. But, an accelerating racket will always have the possibility of catching up with the non-accelerating ball, resulting in multiple bounces. Double hitting occurs often when the exiting velocities are close.

The problem of touch requires that after the impact of the finger and a surface, the finger does not bounce off the surface. Prolonged contact in sports and touch share the same principle in physics. In terms of bounce, touch is collision without bounce. Touch deals with low impact velocity and a non-moving surface, and prolonged contact, with the more general situation of high impact speed and both impacting objects moving. Touch is permanent prolonged contact at low velocity. The following **Figures 2** gives a zero-th order graphic description of prolonged contact. Most pertinent physics of prolonged contact can be extracted from the zero-th order description.

Figure 2 shows the basic elements of velocity and acceleration involved in an impact between a ball and a racket. Velocity and acceleration are drawn with respect to time. When the ball contacts the racket, the ball's negative velocity starts to change to zero and then to positive. The acceleration due to the spring force on the ball changes from zero to maximum to zero. Timing is of essence in prolonged contact. The ideal time to apply acceleration is when the ball velocity is the same as the racket velocity. The ideal jumpulse should be equal to the spring force existed at this ideal time. Jumpulse is a sudden finite change of applied force, which is used to produce the sudden increase of acceleration. As the result of the application of jumpulse, **Figure 2** shows that the ball and racket move with the same velocity and the same acceleration. As an application of the graphic analysis from **Figure 2,** it can be shown that lowering the racket velocity can lower the required acceleration for prolonged contact because the smaller relative velocity between the ball and the racket will produce a smaller indentation and a smaller spring force in the impact.

Position, Velocity, and Acceleration of the Ball and the Racket versus Time

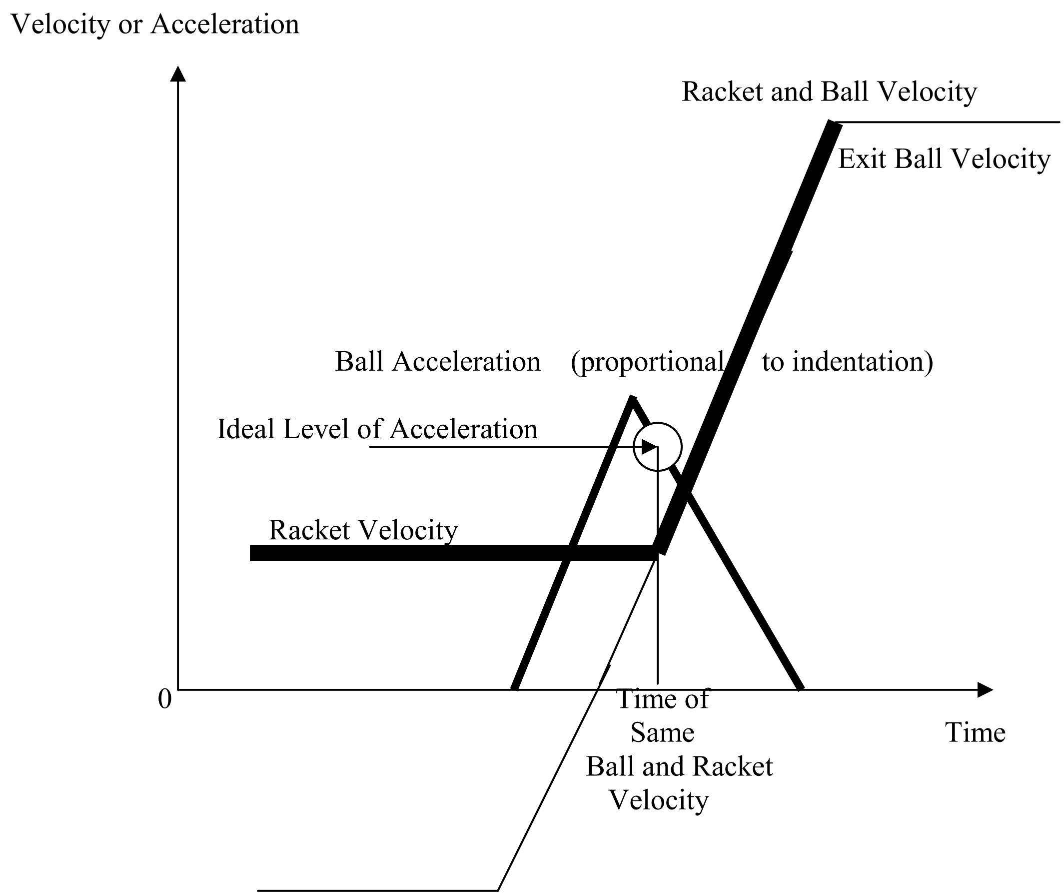


Figure 2 Prolonged Contact

In **Figure 2**, if the bold line for Racket Velocity is below, instead of coincident to, the ball velocity, the line will eventually surpass the exit velocity line for the ball. Thus, the greater velocity of the racket than the ball will enable the racket to catch up with the ball to create the multiple bounced or double hitting. In a realistic situation, double hitting requires that the position and velocity of the ball and the racket be close, not necessarily exactly the same. Prolonged contact has this same requirement, plus the requirement of sufficiently precise timing. Double hitting is just as hard to achieve as prolonged contact, but has the advantage in practice in telling a player by the multiple bounces that the player has almost satisfied the requirement of prolonged contact. In particular, the most difficult requirement of the same velocity is satisfied.

The Mathematics of Double Hitting: Jumpulse Physics
Motion without spin and aerodynamic effects is sufficient to describe jumpulse and its effect. The fundamental equation of the translational interaction of a ball with a racket describes a system of masses, springs and dampers

$$M_b\, d^2R_b/dt^2 \; + \; l \; d(R_b - R_o)/dt \; - \; M_b\, g \; + \; k\,(R_b - R_o) = \text{Applied Force} \quad \text{(Eq. 1)}$$

where $R_b(t)$ is the position of the ball of mass M_b, and $R_o(t)$, l, k and g are, respectively, the position of the ball when the ball is just touching the surface and the spring force is zero, the equivalent damping coefficient, the equivalent spring constant, and the gravitational deceleration. In general, l and k are functions of R_b and t. For quantitative values, realistic averaging methods should be used in determining l and k. Often an approximation allows l and k to take on two or three different constant values during the course of one interaction. Because of the nature of R_b, even this simplified problem cannot always be subjected to analytical description. Approximations should be made for each individual case.

From the close relationship between the ball and the surface, R_b can be written as

$$R_b(t) = R(t) + r(t) \qquad \text{(Eq. 2)}$$

where R(t) is constant relative to the position of a non-deformable surface, and r(t) is the position of the ball relative to R(t). Substituting Equation (2) into Equation (1) and for simplicity, neglecting gravitation and assuming that the motion is one dimensional, Equation (1) becomes

$$M_b\, d^2X/dt^2 + l\, d(X - X_o)/dt + k(X - X_o) + M_b\, d^2x/dt^2 + l\, dx/dt + kx = F \quad \text{(Eq. 3)}$$

using the coordinate shown in **Figure 3,** where F is the Applied Force.

A very important practical application of Equation (3) to be noted is that the nature of X(t) may have significant effect on ball control. For clarity, the stationary coordinate in **Figure 3** is introduced. The shaded area represents a non-deformable (real or imagined) surface such that X(t) is always a constant distance from this surface. We choose X(t) to be equal to $X_o(t)$, the position of the ball when the ball is just touching the surface and the spring force is zero. Furthermore, for the sake of illustration we assume that the damping force is insignificant. Then, Equation (3) simplifies to

$$M_b\, d^2X/dt^2 + M_b\, d^2x/dt^2 + kx = \text{Applied Force} \qquad \text{(Eq. 4)}$$

When the surface is stationary and we let $X=X_o$, we obtain from Equation (4) a natural frequency

$$\text{Frequency} = (1/2\pi)\ \{(k/M_b) - (1/2M_b)\}^{1/2} \qquad \text{(Eq. 5)}$$

which gives an idea of the interaction time, neglecting the damping force and the Applied Force. Equation (4) will be used to illustrate the phenomenon of ball control. At time t=0, the ball with a velocity V_b touches the surface of the racket, which is moving at an opposite direction with a velocity v_r, and that the perpendicular component of the relative velocity between the ball and the racket is, using the coordinate shown in Figure 3,

$$v = |v_r - v_b| \sin\theta \qquad \text{(Eq. 6)}$$

where θ is the angle between the surface and the ball's trajectory. The solution of Equation (4) when the racket is held stationary during the entire interaction is for

$\pi/\{k/M_b\}^{1/2} \geq t \geq 0$, $d^2X_0/dt^2 = 0$ and

$$X_b = X_0 - v_0/\{k/M_b\}^{1/2} \sin(\{k/M_b\}^{1/2} t) \qquad \text{(Eq. 7)}$$

X actually describes the position of the racket. If one accelerates one's racket after $\pi/\{k/M_b\}^{1/2} \geq t \geq 0$ with a constant acceleration

$$d^2X/dt^2 = a_r \qquad \text{(Eq. 8)}$$

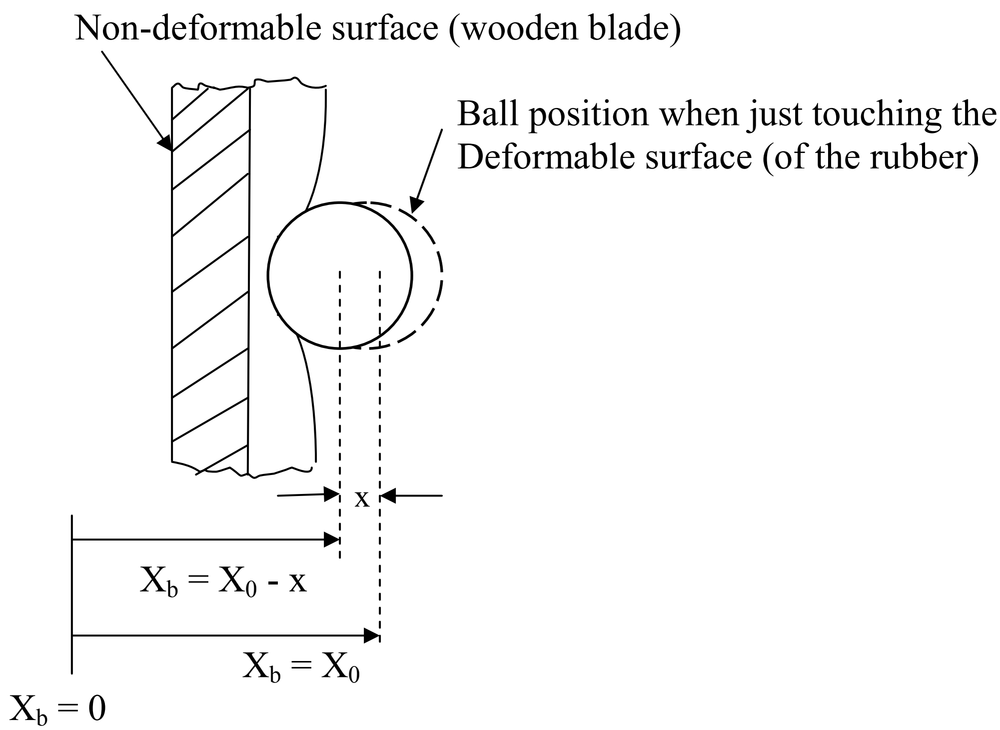


Figure 3 Coordinate Describing the Interaction of a Ball and a Surface

Equation (4) can be written as

$$M_b\, d^2x/dt^2 + k(x - M_b a_r/k) = 0 \qquad \text{(Eq. 9)}$$

Thus, the position of zero force becomes

$$X_b = X_0 - M_b a_r/k \qquad \text{(Eq. 10)}$$

and the amplitude of oscillation is $|v_m\{M_b/k\}^{1/2}|$ where v_m is the maximum speed of the ball relative to the racket after the introduction of the acceleration and also the speed of the ball when it is at the position of zero force.

The position of zero force has been moved back from $X_b = X_0$ by a distance $M_b a_r/k$. When $M_b a_r/k$ is greater or equal to the amplitude of oscillation, $|v_m\{Mb/k\}^{1/2}|$, the ball will remain in contact with the racket. Thus, in order to keep the ball on the racket the following relation must be satisfied:

$$a_r = |v_m\{k/M_b\}^{1/2}| \qquad \text{(Eq. 11)}$$

where v_m also depends on a_r, and can be found by solving the appropriate equation of motion. Physically, Equation (11) results from the fact when the amplitude of oscillation is smaller than the displacement of the equilibrium position where the force is zero, the ball will remain in contact with the racket. The only time in which a player can exert control over the subsequent trajectory of the ball is when the ball is in contact with the racket. The additional time of contact will allow the player greater opportunity to adjust to the player's desired shot.

To make the analysis more complete, the motion for $a_r <> |v_m\{k/M_b\}^{1/2}|$ should also be described. If $a_r <> |v_m\{k/M_b\}^{1/2}|$, the ball may move alternately in and out of the racket. If one accelerates the racket, there is always a period during which the acceleration must decrease to a value less than $|v_m\{k/M_b\}^{1/2}|$, and then the ball has a chance to move in and out of the racket. Almost all sports, except tennis, outlaw double-hitting, and this regulation is in conflict with physics. After this research, the field of sports regulations should be modified in accordance with physics, and the sports manufacturing industry could be revolutionized by jumpulse.

Physics of Collision

When a ball collides with a racket in the hand of a player, the mass of one of the two colliding bodies, namely, the body associated with the racket depends heavily on how hard the player grips the racket and whether the contact is in front, on the side, behind the player, the weight of the player, etc. The problem of collision is further complicated when one tries to determine the velocity of the racket right after the collision, which involves jumpulse.

Before the concept of jumpulse is formalized, it would be difficult to give a formal physics description of collision. The starting point of physics description is the conservation of energy and momentum. Since the final velocity of the racket depends on jumpulse, the full description of collision misses the essential concept, namely, jumpulse.

The equations of conservation of momentum and energy, where V is capitalized to represent the velocity after the collision:

$$m_b v_b + m_r v_r = m_b V_b + m_r V_r \quad \text{or} \quad V_r = m_b v_b/m_r + v_r - m_b V_b/m_r$$

$$m_b v_b^2/2 + m_r v_r^2/2 = m_b V_b^2/2 + m_r V_r^2/2 \text{ or } m_b v_b^2 + m_r v_r^2 = m_b V_b^2 + m_r V_r^2$$

Substituting

$$m_r V_r^2 = m_r(m_b v_b/m_r + v_r - m_b V_b/m_r)^2$$
$$= m_r(m_b v_b/m_r)^2 + 2m_b v_b v_r - 2m_b^2 v_b/m_r + m_r v_r^2 + 2m_b v_r V_b + m_b^2 V_b^2/m_r$$

into the equation of conservation of energy

$$m_b v_b^2 + m_r v_r^2 = m_b V_b^2 + m_r V_r^2$$

and collecting terms, we get:

$m_b(m_r+m_b)V_b^2-2(m_b^2v_b+m_bm_rv_r)V_b+(m_b^2v_b^2+2m_bm_rv_bv_r-m_bm_rv_b^2) = 0$

which is a quadratic equation, a second degree polynomial equation. Solving for V_b and V_r gives:

$V_b = ((m_b - m_r)v_b - 2m_rv_r)/(m_b + m_r)$ and $V_r = ((m_r - m_b)v_r - 2m_bv_b)/(m_b + m_r)$

If $m_r >> m_b$, $V_b = ((m_b - m_r)v_b - 2m_rv_r)/(m_b + m_r) \sim -(v_b - 2v_r)$ and $V_r = ((m_r - m_b)v_r - 2m_bv_b)/(m_b + m_r) \sim v_r$

The above formula checks with the intuitive observation of the collision between a ball and a solid moving wall. When a jumpulse is applied and the grip is firm, the effective mass of the racket can approximate a solid moving wall $m_r >> m_b$; $V_r \sim v_r$. The rebounding speed of the ball can be the sum of the absolute speed of the ball plus the speed of the racket. Without the concept of jumpulse, the physicists have, thus far, been unable to explained collision without bounce.

The mass of the racket roughly, still with validity, can be assumed to be very large in a jumpulse stroke. To determine the velocity of the racket, we think the physical picture of the interaction of a ball with a force field, created by the spring of the racket and the jumpulse or acceleration.

Relationship to Newtonian, Lagrangian, Gibbs-Appell, and Hamiltonian Mechanics

The concept of jumpulse is really an extension of the Newtonian concept of impulse. Theoretically, the derivatives should not stop at the second order, as in Appell function and Gibbs-Appell Equation. But the mathematical description is after the fact, whereby only second order derivative seems to be significant, ignoring all higher derivatives, as in Langrangian and Hamiltonian Mechanics. Mathematics should have its own merit independent of the physical part of the reality. In kinetic theory, especially for plasma physics, only the Generalized Fluid Description, which generalizes prolonged contact, gives a full description of plasma fluid:

$$\frac{DF}{Dt} \equiv \frac{\partial F}{\partial t} + \dot{x}\frac{\partial F}{\partial x} + \ddot{x}\frac{\partial F}{\partial \dot{x}} + \dddot{x}\frac{\partial F}{\partial \ddot{x}} + \ldots + x^{(\text{n dots})}\frac{\partial F}{\partial x(\text{n}-1\text{ dots})} + \ldots + \infty$$

where F is further generalized to be a distribution function of arbitrary objects in the generalized phase space of infinite dimensions. The description needs to be combined with the equations of motion to be applicable. With jumpulse, Equation (4) becomes:

$$M_b\, d^2X/dt^2 + M_b\, d^2x/dt^2 + kx + J = 0 \qquad \text{(Eq. 12)}$$

where J changes instantaneously from 0 to $a_r = |v_m\{k/M_b\}^{1/2}|$ during the moment of impact. Jumpulse is a step function in the force vs. time graph. Its time derivative is infinite and would be difficult to describe analytically. Realistic phenomena should generally be calculated numerically with difference equations and, thus, should be formulated numerically, using the above equations or Gibbs-Appell Equation with energy of acceleration for the planned computer simulation of jumpulse in this proposal.

III. Relation to Present State of Knowledge

Hugh Ching, the Principal Investigator of this proposal, solved the problem of prolonged contact in sports as the secret of consistency in sports as early as 1968. In his 1978 book **Table Tennis Scientific Analyses** [Ref. 5], he predicted double hitting as a consequence of prolonged contact.

In the early 1980's, the tennis regulation changed to allow double hitting, as long as it is done within one smooth stroke. Ta-You Wu formalized the solution of touch with the concept of jumpulse to denote a sudden change of force and published a paper [Ref. 2] in 2000, defining jumpulse. Ching modified the definition of jumpulse with the Law of Touch, which states "Uunlike position and velocity, which requires time to change, acceleration, force, and jumpulse, which must occur within the short time interval of an impulse, can change instantaneously."

Mandal and S. Payandeh, in their paper "**Control Strategies for Robotic Contact Tasks: an Experimental Study**" in JJ of Robotics Systems, v. 12, no. 1, p 67-92, 1995 pp. 68 third paragraph states "Due to contact instability, even apparently simple contact tasks proven to be surprisingly difficult. ..." [Ref. 7]. S. Payandeh and M. Saif, in their paper "**Force and Position Control of Grasp in Multiple Robotic Mechanism**" J. of Robotics Systems, v. 13, no. 8, p 515-525, 1996 also states the difficulty in dynamic contact [Ref. 8].

Paul F. Jacobs, in his paper, "**Stereolithography and other RP&M Technology, from Rapid Prototping to Rapid tooling**" Society of Manufacturing engineers, 1996 pp. 113 at Figures 3.18 and 3.19 at the bottom states "... As shown in this figure, the actual path significantly overshoots the command trajectory." [Ref. 9] The implication of this finding is that sharp turns with negative rate of increase of the radius of gyration, essentially, a jumpulse-like motion, could improve the situation.

K. B. Shimoga and A. A. Goldenberg, in their paper, "**Soft Robotic Fingertips: Part I: Comparison of Construction Materials**" Robotics Research, v. 15, no. 4, pp. 320-334, August 1996 [Ref. 10] and K. B. Shimoga and A. A. Goldenberg, in their paper "**Soft Robotic Fingertips: Part II: Modeling and Impedance Regulation**" Robotics Research, v. 15, no. 4, pp. 335-350, August 1996 [Ref. 11] both parties show the materials can soften the impact, but might not achieve total elimination of bounce.

M. Aicardi, G. Casalino, and G. Cannata, in their paper, "**Contact Force Canonical Decomposition and the Role of Internal Forces in Robust Grasp Planning**" Robotics Research, v. 15, no. 4, pp. 351-364, August 1996 [Ref. 12] and R. M. DeSantis, in his paper, "**Motion/Force Control of Robotic Manipulators**" J. of Dynamic Systems, Measurement, and Control, v. 118, pp. 386-389, June 1996 [Ref. 13] both parties shows additional force is needed in achieving dynamic contact without bounce. Howard Brody, in his paper, "**How Would a Physicist Design a Tennis Racket ?**" Physics Today, pp. 26 -31, March 199 (page 27 middle of right column "... Because control is not a well-defined term, ..." [Ref. 14] indicates that prolonged contact is not realized as the secret of consistency. PI Hugh Ching, in his book, **Table Tennis, Scientific Analyses**, [Ref. 5] Sports Scientific Design 1978 pp. 31 bottom states "... It would not be totally absurd to suspect that double hitting is much more often than have been called; the international rule of table tennis regarding double hitting should probably be modified."

J. L. Groppel, J. E. Loehr, D. S. Melville, A. M. Quinn, in their book, **Science of Coaching Tennis**, [Ref. 15] Published by Leisure Press, 1989 pp. 30 middle state "...It is, of course, impossible for any player to `hold' the ball on the strings during a stroke." Similar sentiments, both for and against, are expressed, for example, by C. L. Vaughan, in his book, **Biomechanics of Sport**, [Ref. 16] CRC Press, 1989 pp. 263 – 288. Robert H. Romer, Editor, in his editorial, "**Editorial: Magnetic monopoles or cross products? Is physics too difficult?**" American J. of Physics, v. 6, no. 12, pp. 1065, December 1993 top right column states "...Physicists have given a name to x-double dots; rarely does anyone take the trouble to give a name to x-triple dots.... I am confident that the physicists in some distant galaxy have a name for x-double dots but probably have not bothered to give a name to x-triple dots." [Ref. 17].

H. P. W. Gottlieb, in his paper, "**What is the simplest jerk function that give chaos ?**" American J. of Physics, v. 64, no. 5, pp. 525, May 1996 at top of the left column again belittles the significance of derivatives higher than acceleration with the statement "The third time derivative of displacement, `jerk,' has attracted little attention because of its relatively unimportance in classical dynamics..." [Ref. 18]. Similarly, J. P. Den Hartog, in his classic, **Mechanics**, [Ref. 19] Dover Publications, Inc. New York, 1948, 1961 near top of pp. 161, second paragraph states "The question might be asked why we stop here, and why we don't keep on differentiating to x-triple dots and higher derivatives. The answer to this, as we shall see in the following chapters, is that the second derivative of the displacement, linear of angular, is of great importance, whereas the third derivative hardly ever occurs in practice. The quantity x-triple dots, the time rate of change of acceleration, has some physical meaning and has even been given a name: it is called `jerk' (Problem 309, page 432) but it is of no particular importance…."

Heinrich Hertz, in his book, **The Principles of Mechanics Presented in a New Form**, [Ref. 20] Dover Publications, Inc. New York, 1956 solves the problem of static contact problem. Ernst Mach, **The Science of Mechanics**, [Ref. 21] The Open Court Publishing Company, Chicago, 1907 has not realized the problem of touch. Rene Dugas, in his very comprehensive and excellent book, **A History of Mechanics**, [Ref. 22] Dover Publications, Inc., New York, 1988 pp. 449 middle states "...Poincare consoles us in the following way. Force is equal to the product of mass and acceleration by definition. Similarly, action equal reaction by definition. These principles are unverifiable, for there are no perfect isolated systems in nature. ..' and has not cover the problem of touch.

Again, L. D. Landau and E. M. Lifshitz,, in their book, **Theory of Elasticity**, [Ref. 23] Pergamon Press, London, Paris, Frankfurt, 1959 and G. M. L. Gladwell, in his book, **Contact Problems in the Classical Theory of Elasticity**, [Ref. 24] Sijthoff & Noordhoff, 1980 does not realized that touch is a problem. Similarly, all the following publications of A. M. Perelomov, **Integrable Systems of Classical Mechanics and Lie Algebras**, [Ref. 25] Volume I, Birkhauser Verlag, Basel, Boston, Berlin, 1990, David Hestenes, **New Foundations for Classical Mechanics**, [Ref. 26] D. Reidel Publishing Company, Holland, 1986, I. Ronald L. Greene, **Classical Mechanics with Maple** " [Ref. 27] m, 1995, and D.Greenspan, **Computer-Oriented Mathematical Physics**, [Ref. 28] Pergamon Press, London, Paris, Frankfurt, 1981 do not realize the problem of touch.

William Shockley and Walter A. Gong, in their book, **Mechanics**, [Ref. 29] Merril Physical Science Series, pp. 64 mentioned the definition wu = weight unit, which is used as the unit for jumpulse, where one newton = one wu. Hawkins and Jones and their article "**Mechanics Simulations, consortium for Upper-Level Physics Software, 1995**" [Ref. 30] can be extended to simulate jumpulse. Henriette S.M. Cramer, Nicander A. Kemper, Alia Amin, and Vanessa Evers, in their presentation, "**The effects of robot touch and proactive behaviour on perceptions of human-robot interactions**" ACM/IEEE International Conference on Human-Robot Interaction, Proceedings of the 4th ACM/IEEE international conference on Human robot interaction, La Jolla, California, USA, SESSION: HRI late-breaking abstracts, Pages: 275-276, 2009 ISBN:978-1-60558-404-1 state in their Abstract "Despite robots' embodiment, the effect of physical contact or touch and its interaction with robots' autonomous behaviour has been a mostly overlooked aspect of human-robot interaction." [Ref. 31] A very serious and practical problem regarding contact still lingers in the design of relays. For example, GIGAVACU published an article "**THE PHYSICS OF VACUUM & GAS FILLED HIGH VOLTAGE RELAYS**" by GIGAVAC, LLC., which shows that to counteract the danger of microscopic vibration during contact of relays, the cumbersome process of using gas and vacuum is necessary [Ref. 32].

People at NASA are still struggling with the problem of touch in relationship to spacecraft docking and space robots. For example, Richard Volpe and Pradeep Khosla published an article "**A Theoretical and Experimental Investigation of Explicit Force Control Strategies for Manipulators**" IEEE Transaction on Automatic Control, Vol. 38, No. 11, November 1993, [Ref. 33], which shows the importance of the solution of touch.

Tennis coaches, most notably Oscar Wegner [Ref. 34], inventor of a method qualitatively similar to the one described in this proposal, and Doug King [Ref. 35], the inventor of Acceleration Tennis, had discussed at length and/or met with post-science students. Most importantly, over the disinterest of physicists and coaches, the professional tennis players are overwhelmingly in support of a post on Tennis.com instruction section [Ref. 36], which has over 65,000 views, in contrast to the next highest viewing number of around 5,000, an order of magnitude smaller. Recent publications[Ref. 37-40], such as Saraf, R.F. Maheshwari, V. Nguyen, C. "**Linear Tactile Nanodevice with Resolution on Par with Human Finger"** Optical MEMS and Nanophotonics, 2007 IEEE/LEOS International Conference on Publication Date: Aug. 12 2007-July 16 2007, M. T. Mason, S. S. Srinivasa, A. S. Vazquez, and A. Rodriguez, "**Generality and Simple Hands**" Robotics Institute, Carnegie Mellon University, Technical Report CMU-RI-TR-10-40, 2010, and Sachin Chitta, Matthew Piccoli and Jurgen Sturm "**Tactile Object Class and Internal State Recognition for Mobile Manipulation**" Forum: ICRA 2010, have involved jumpulse without knowing the theory and can be greatly improved; they support the claims in this proposal.

IV. Goals and Characteristics of Research

The main goal of this research is to verify with physical experiments the phenomenon of prolonged contact. There is already one successful experiment with PASCO [Ref. 41], which supplied the equipment of two colliding model cars [Ref. 42]. This research will have the personal backing of the President of the sponsoring university with the entire student body and the educational participation of over 80 associated universities in his Global Educational Consortium (GEC). The diversified research and educational groups in computer science, physics, and engineering will make the whole research far greater than its separate components. In particular, combining old data in sports and new concepts in physics has made the final value of the solution of touch far greater than the sum of the values of the individual two contributors.

V. General Plan of Work with Budget Allocation: Timeline, Schedule, and Budget

The initial phase of the project will be the research and the education of the solution of prolonged contact, from which the design of computer simulation and physical experiments will be planned. The PI will spend 20% of his time for a year starting tentatively on April 15, 2012. One laboratory technicians, one programmer, one technical writer with knowledge of physics, and one secretary will assist in, respectively, the performance of the physical experiments, the computer programming of the simulations, the publication of a technical manual for the experiment of the Jumpulse Mechanism, and clerical work. The advantage of working with PASCO is in the broad educational impact of the jumpulse experiment, which can be distributed world-wide through the global educational marketing reach of PASCO. The total budget with $204,160 for salaries and $146,925 for other expenses is $351,085.

The simulations of the Jumpulse Mechanism will be done using scientific and web software systems, such as Matlab, physics engine, Java, the "Singular" package, which can be interfaced from GAP, Groups, Algorithms and Programming. As a simple example of simulation, collision of two blocks, one of which is connected to a spring [Ref. 43], is given to show that without the jumpulse mechanism, the two blocks will always bounce off each other.

The main and the most costly equipment for the research will be a Fastcam SA5, or an equivalent similar setup. The high-speed video camera, which is sufficient for videotaping collisions in sports, costs of $96,925. The video camera will be now and in the future a crucial equipment to prove the theory of prolonged contact based on jumpulse and to convince the sports world the existence or prolonged contact. The 7000+ fps (frames per second) camera can capture about 70+ frames in 10 milliseconds with the interaction time expected to be from 4 milliseconds to 8 milliseconds. Roughly the 70 frames can show as a regular 30 fps for 3 seconds of ultraslow motion video on the web with 32 GB of memory. The original video data will be accessible by the public through ftp stream to their own servers or computers or on disks. The ultraslow motion display will be downloaded to YouTube for the public. The search for and the learning to use possibly one of the fastest video cameras will take up the first few months of this research. PI has extensive experience in high-speed camera and their performances gained from past interactions with sports coaches and researchers. The intensive public debate also heightens the interest.

The sponsoring university will supply the office spaces, Internet access, and phone service. There will be plans for attending meetings and conferences. The funding will also be used for cost of equipment and fees related to the publication of papers on the subject. Total Budget is $351,085.00 lasting for one year, starting April 15, 2012. PI will devote 20% time at $100 per hour for a total of $41,600. The salaries of three or more part-time professionals at $40 per hour and one half-time secretary at $30 per hour add to a total of $204,160, including 10% fringe benefit. Additional $146,925 will be used for equipment ($102,925), travel ($6,000), material and supply ($6,000), publications ($6,000), computer service ($6,000), consulting fees ($6,000), and participant support ($14,000). The tentative budget schedule is: First Quarter (4/15-7/15 2012) Purchase equipment and software; Preparing the experimentation and simulation; Applying to relevant domestic conferences; Hiring assistant/programmer/secretary ($160,000); Second Quarter (7/15-9/15/2012) Performing the experiment and developing simulation software; Video Taping and publishing the Jumpulse Mechanism; Starting Communication with relevant parties ($60,000); Third Quarter (9/15-11/15/2013) Continuing the experiment and simulation; Preparing publication and attending conferences ($60,000); Fourth Quarter (11/15/2012-4/15/2013) Writing and releasing the final reports based on feedback ($71,085). Details are in Budget Justification.

VI. Intellectual Merit and Broader Impacts with Transformative Potential

In terms of broad educational impact, all the schools from kindergarten to postgraduate will learn jumpulse for prolonged contact, the secret of consistency in sports, in their physical education and physics classes. The concept of jumpulse will instantly affect all the students and professionals in sports. This proposed research should capture the attention of the world with advancement in understanding, explanation, and demonstration of the relevant knowledge of touch. This research will open up a broad spectrum of research relating to the effect of a force applied during collision.

This proposal raises a most fundamental concept regarding how motion starts. The concept can be illustrated with two scenarios. The first scenario is that motion starts from a gradual increase of acceleration from zero due to jerk, and when the acceleration become finite, velocity will increase from zero due to the finite acceleration, and position changes due to the velocity. The second scenario is that motion starts from a finite acceleration, skipping the first stage of increasing the acceleration from zero due to jerk. The second scenario is far more efficient than the first, but becomes almost essential in prolonged contact or touch, in which the two colliding bodied must instantaneously assume the same acceleration. The second scenario is to be tested in this proposal and could lead to a transformative change in the basic understanding of motion.