JTS
Journal of Taiji Science
Vol.1 Iss.1 / June / 2022
Digital Edition: ISSN 2832- 062X
Print Edition : ISSN 2832-0611

Biomechanical Analysis of Taijiquan Martial Application

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***Abstract*—**Taijiquan can handle incoming forces with minimal effort and it can overcome hardness with softness. This claim is sometimes viewed suspiciously because ordinary people cannot execute the internal force of Taijiquan. Relaxation can enhance stability and rooting can help facilitate self-defense. This claim often causes confusion because ordinary people are unfamiliar with these concepts. In the following, the author cites ancient Taijiquan Classics and reviews scientific literature to discuss a better way for Taijiquan training for health, and to help reveal an effective way of Taijiquan application for self-defense. Martial application is a complex process, and involves converting the mechanically disadvantaged systems in the human body to be more efficient and effective mechanisms. As a martial art for self-defense, Taijiquan is most challenging for practitioners when it comes to quickly receiving a strong oncoming force and effectively launching "*Jin*" after neutralization. The biomechanical aspects of Taijiquan martial art are evaluated in terms of motional control; the six degrees of freedom in motion; maintaining a central equilibrium; biotensegrity formation; the living fulcrum and leverage utilization; ground reaction force enhancement; and body kinetic chain manipulation. In this paper, the mysterious "Qi" and "*Jin*" are scientifically defined, to help users understand the essence of Taijiquan.

Keywords: Taijiquan, biomechanics, martial application, internal force, relaxation, central equilibrium, body integration, biotensegrity, levers, ground reaction force, kinetic chains

Introduction

Taijiquan is a martial art based on the principles of changes (Taoism) and the practice of constant equilibrium (Confucianism). After more than 400 years of evolution, the meditative aspect of Taijiquan is recognized for both maintaining mental and physical health (in terms of relieving stress and maintaining homeostasis), and creating a unique, soft-style martial art. We are fortunate that the ancient Taijiquan masters left us several precious Taijiquan Classics, which cover the underlying Taiji philosophy and methods of practice for martial application. Before the mid-1930s, the Taijiquan Classics were passed down in secret, from generation to generation within individual lineages. Now these Taijiquan Classics are open to the public as the single authoritative guide for developing martial skills. From the historical viewpoint, the prestige and influence of Taijiquan came from its unique martial arts. Thus, the martial art aspects are the most quintessential part of Taijiquan.

In modern literature, Time Magazine has called Taijiquan "the Perfect Exercise"[1], and the Cable News Network has described Taijiquan as being "Medicine in Motion".[2] Taijiquan's health benefits can be further reinforced when the technique's martial abilities are achieved by the practitioners.

To master the essential martial arts, Taijiquan practitioners must abide by all requirements of the Taijiquan Classics. However, the problem is these texts are written in literary Chinese, and they are mainly expressed in metaphors, which makes the translation of the Taijiquan Classics a difficult task for a translator who has not yet acquired a high-level of martial skills. As can be imagined, most of the

DOI: 10.57612/2022.JTS.01.02

Vol.1 Iss.1 / June / 2022
Digital Edition: ISSN 2832- 062X
Print Edition : ISSN 2832-0611

translators are not experts of Taijiquan. It is therefore important to address this problem.

It is also only in the last few decades that biomechanical research into Taijiquan has become possible, but these studies mainly address the health benefits. The purpose of this article is to explain the most critical martial characteristics of Taijiquan from a biomechanical viewpoint, which will help serve as a scientific basis to support the principles of Taijiquan Classics for self-defense.

Building A Martial Arts Foundation for Six Degrees of Freedom in Motion

There are six traditional lineages of Taijiquan; plus several other standardized styles, which were promoted after 1956 for mainly health purposes. Every postural movement of Taijiquan, especially for those six traditional styles, is intended for martial application. So, if the practice methods are inconsistent with the requirements of the Taijiquan Classics, the practitioner will often perform the moves merely as a type of physical, mechanical exercise, without truly comprehending the skills used in self-defense.

In ancient times, Taijiquan was originally called Thirteen Postures (after the Eight Gates and Five Steps). All movements, in all current styles of Taijiquan, are based on these basic thirteen postures, with slight differences in their arrangements and permutations.

The Eight Gates, which are ward-off (掤), roll-back (捋), press (挤), push (按), pull-down (採), split (挒), elbow strike (肘), and shoulder strike (靠); all refer to movements of the upper limbs, and express the laws of changes in eight directions (four cardinal and four diagonal).

The Five Steps, which are advance (前进), retreat (后退), look left (左顾), look right (右盼), and central equilibrium (中定); refer to the lower limbs, and they express the principle of footwork.

Among the basic thirteen postures, central equilibrium is the most important, and all other twelve postures must have the central equilibrium component within them.

Biomechanically, a simple explanation of the “Five Steps" is that the legs are responsible for attacking, retreating, dodging, advancing, and maintaining central equilibrium; and each footwork controls the motions of six degrees of freedom (3 rotational and 3 translational). These then allow for any necessary self-defense actions.

Thus, for martial arts, leg training is important. As stated in the Taijiquan Classics: “*If timing and position are not appropriate, the body will become disordered, and adjustments must be sought in the legs and waist* (有不得机势处，身便散乱，其病必于腰腿求之)”.[3]

Accordingly, in Taijiquan the priority of leg training should be placed on muscle tone over muscle growth, to maximize the six degrees of freedom in motion. With proper training, the entire body is free to change its position through forward/backward, up/down, and left/right translation in three perpendicular axes, which are then combined with changes in orientation, through rotation about three perpendicular axes (these being yaw, pitch, and roll (see Figure 1)).[4]

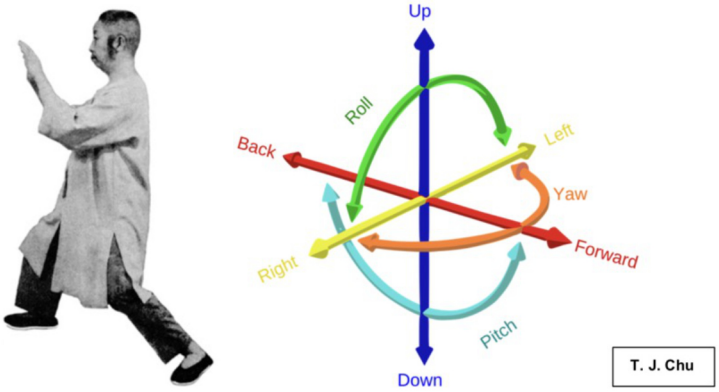

Fig. 1 Six degrees of freedom in the lower limbs (hips, knees, ankles, feet) during Taijiquan movements.

DOI: 10.57612/2022.JTS.01.02

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Biomechanically, a simple explanation of the Eight Gates concept is that the arms are an extrapolation on the idea of the insubstantial (Yin) and substantial (Yang) changes, along with the eight types of actions added onto the six degrees of freedom in the legs.

The movements of the upper and lower limbs are coordinated through the body kinetic chain, but the lower limbs control the motion of the upper limbs. Thus, in addition to the power of the legs, a Taijiquan practitioner can use various types of actions to cope with any potential threat (for example, to ward-off a blow in any of the four cardinal directions involving linear momentum and pressure; or to roll-back in any of the other four ordinal directions involving angular momentum and torque).

In Taijiquan, it is critical that the role of the arms is limited to regulating the body's alignment; and to aiming or reaching out to the target. The arms should not be used to apply piecemeal or unintegrated forces, because all the joints in the arm are considered Class-3 levers, and provide negative mechanical advantages. For these reasons, advanced Taijiquan practitioners don't apply piecemeal forces from the arms to interfere with the leverage of the integrated ground reaction force (GRF) from the feet. (More discussion on this is provided in later sessions). This is consistent with Master Cheng Man-Ching's statement that: "*Taijiquan is without hands, and hands on is not Taijiquan* (太极拳不动手，动手非太极拳)".[5]

Outsmarting the Response to the Fear of Fighting

In any real situation facing an immediate physical threat, martial artists have all battled against the fears that arise at the beginning of a fight. The result is often a reaction within the amygdala (the part of the brain in the cerebral hemisphere that is involved with experiencing emotions), which is apt to flip individuals into a fight-flight-or-freeze mode, in response to an immediate threat.

This also triggers the release of stress hormones that prepare the body to fight the threat, or to flee from the danger.

During the height of the fight-flight-or-freeze response, the routine diaphragmatic breathing of the Taijiquan practice can be a powerful tool to take control away from the amygdala, and hand it back to the hippocampus and prefrontal cortex; which can control the fear response in a rational way.

As diaphragmatic breathing slows down the breathing process, and sends signals to the brain that the situation is not alarming; the body stops producing the neurotransmitters and hormones responsible for fear and anger emotions.[6] It has been demonstrated that Taijiquan intervention has a strong effect on neuroplasticity by increasing gray matter volume and the enhancement of functional connectivity.[7] Compared to other regions of the brain, the hippocampus is more susceptible to neuroplasticity.[8] Thus, the neuroplasticity from proper Taijiquan training to acquire a psychological advantage over a bigger and stronger opponent can mitigate the emotional fear response.

Accordingly, Master Cheng Man-Ching indicated that those Taijiquan practitioners who wanted to excel in self-defense must have three characters of fearlessness: (1) fearlessness of enduring the long training required for rooting, (2) fearlessness of suffering losses while investing in yielding, and (3) fearlessness of facing ferocity as softness can overcome hardness.[9]

The first two characters are prerequisites to the third character, which is essentially the ability stemming from better relaxation from routine performance of diaphragmatic breathing. The first character of fearlessness entails long-term practice that causes changes to occur in the structure of the brain, which strengthen the neural connections, and improve cognitive skills. Diligent Taijiquan practitioners, with improved neural efficiency, can maintain lower activity levels in the sensory and motor cortex, with less energy expenditure and more effective outcomes.[10] The second character of fearlessness requires the Taijiquan practitioners to learn from prior sacrifices and losses to gain the four crucial keys of Taijiquan techniques: touching (沾), sticking (粘), connecting (连), and following (随) for effective self-defense.

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Enhancing the Neuromusculoskeletal Control by Diaphragmatic Breathing

The traditional Taijiquan training with diaphragmatic breathing affects the whole-body system by not only stimulating the phrenic and vagus nerves for regulating the peripheral nervous system but also strengthens core muscles via an increase of intra-abdominal pressure (IAP) for proper load balancing of the pelvis and spine throughout the body kinetic chain.[11] The Taijiquan movements with mindfulness and relaxation help mediate neuromusculoskeletal responses through activating the parasympathetic nervous system and calming down the sympathetic nervous system.

The Taijiquan Classics indicates: "*Effortlessly the Jin reaches the head-top, while letting the Qi (sensation) sink to the Dantien (abdomen)* (虚领顶劲，气沉丹田)".[12] This implies that Taijiquan is an effortless action when manifested by diaphragmatic breathing along with correct postural alignment, mindfulness meditation, and rooting in connection with the ground beneath the feet.[13] While the spine and the head naturally held upright as guided by the mind, the diaphragmatic breathing can accelerate the circulation of cerebrospinal fluid.[14] The cerebrospinal fluid plays an essential role in maintaining the homeostasis of the central nervous system.

Accordingly, the triple function (breathing, peripheral nerve regulation, and core stabilization) of the diaphragmatic breathing is a vital part of traditional Taijiquan training.[13] In this case, the core is the muscular cylinder (see Figure 2). While sinking the Qi down to the Dantien, the diaphragm serves as the roof of muscular cylinder, whereas the pelvic floor serves as the floor, and the transversus abdominis and multifidus muscles serve as the wall.[13]

Contraction of the diaphragm downward increases IAP within the muscular cylinder, thus adding to

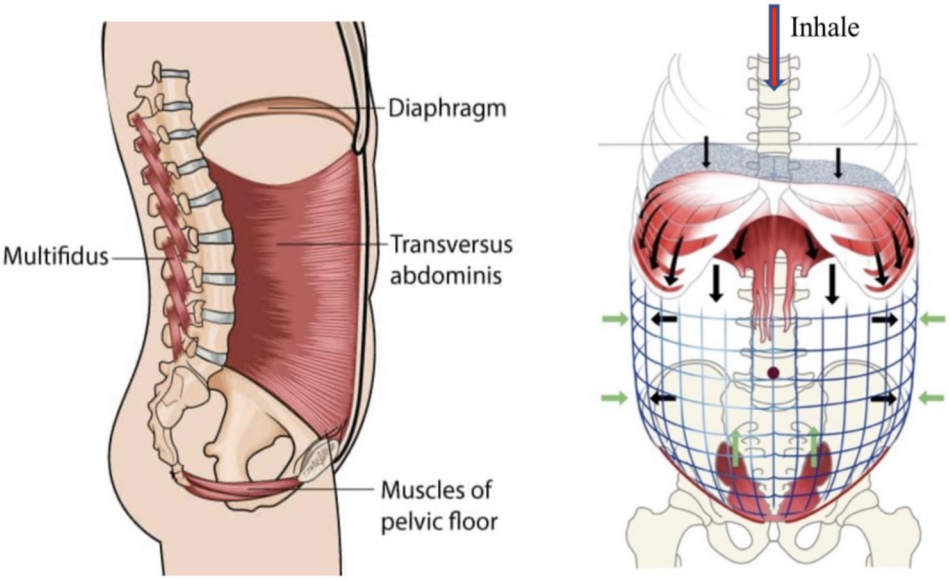

Fig. 2 Diaphragmatic breathing for core and lumbar stability as Muscular Cylinder.
[Image courtesy of Healthwise Inc. and Prague School of Rehabilitation]

spinal stability.[15] In addition, diaphragmatic contraction increases stability of the trunk by minimizing displacement of the abdominal contents into the thorax and maintaining a hoop-like geometry of the abdominal muscles, which increase spinal stability through tension in the thoracolumbar fascia.[16] Moreover, through the diaphragm's fascia and connective links, the diaphragmatic breathing can activate the thoracic and lumbar erectors, internal and external obliques, quadratus lumborums in the lower

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back, and the psoas muscle that crosses the rim of the pelvis to connect the legs to the spine.[17]

In conjunction, these are all important muscles to stabilize the innermost load-bearing structure – the spinal column. The contraction and strength of these deep muscles are enhanced by the presence of IAP, and the increased pressure provides a stable structure for maximal force production and structural integrity. Therefore, these small and large muscle groups are dependent upon each other for optimum function. From a neuromusculoskeletal perspective, the alignment of the body structure and diaphragmatic breathing have a very direct impact on the function of those core muscles for spinal stabilization.

Exploring the Arts of Receiving

According to the Taijiquan Classics, progressive martial art ability is developed as follows: *"From familiarity with the correct postural processes, one gradually comprehends Jin; from the comprehension of Jin, one can reach wisdom. Without long practices, one cannot suddenly understand it* (由著熟而渐悟懂劲，由懂劲而阶及神明；然非用力之久，不能豁然贯通焉)".[12] This means it requires extensive practice of correct postures to become familiar with all the principles of the Taijiquan Classics, and to gain the proprioceptive sense and kinesthetic abilities prior to acquiring *Jin*.

Proprioception (an awareness of the position and movement of the body) results from sensory receptors in the nervous system and the body, which are mostly located in the muscles, joints, and tendons; whereas kinesthetic sensations are derived from sensory receptors in the muscle, skin, and joints as well as from central signals related to motor output. This means comprehending *Jin* requires an extensive effort to excel in touching, sticking, connecting, and following an opponent, and then to be able to yield and neutralize their moves with ease, comfort, and least effort. As with many endeavors, there are different levels and stages in comprehension before it is possible to fully understand *Jin*. Advanced *Jin* involves deep interoceptive and proprioceptive awareness, to control both motion and stillness, and to maintain homeostatic conditions in fighting.

Interoceptive signals arise from many different physiological systems of the body. So, the comprehension of *Jin* relates to mastering and applying various kinds of mechanically efficient GRF and torques while engaged in sensing, yielding, controlling, receiving, and/or launching.

Among all Jins that are developed for use in Taijiquan, for martial applications, the most difficult one to master in free fighting is the receiving *Jin* (which relates to the ability to absorb an incoming force).[18] This can be considered the essential secret of Taijiquan, but it is rarely discussed in the Taijiquan literature. One of the few references to this mystery was discussed by Master Cheng Man-Ching, who stated that if your achievement reaches this level of "receiving *Jin*", then you do not have to worry about other kinds of *Jin*.[18]

His explanation of receiving *Jin* is analogized as follows. Imagine someone throws a ball to hit another person. If the receiver resists the ball or hits it, it will bounce out. This description is the *Jin* of colliding, and is not a receiving *Jin*.

The receiving *Jin* means the receiver is able to catch the ball and is then able to toss it out, regardless of the speed and weight of the ball. This requires the skills of sticking (moving in contact with the opponent to take control), sensing, lifting, and discharging to enable both the catching and discharging to occur almost simultaneously. Since the power can be intensified quickly in a narrow space, it indicates the highest wisdom in free fighting. According to Master Cheng Man-Ching, besides the receiving *Jin* as the ultimate supreme capability of Taijiquan, there is nothing else.[18]

So, what is "receiving *Jin*?" This is when someone attacks with sudden motion, and no matter whether the attacker makes contact with your hands or another part of your body, all you think about doing is nothing but "relaxation. Regardless of how the attacker feels about the touch of your body, whether it is hard, or soft movement combined with hard, your effort is not piecemeal. You relax to neutralize the incoming attack by forming a biotensegrity framework, and use the support of GRF that runs from your feet through the legs, waist, and chest to the arms.

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If the oncoming attack is a force resulting from a Class-3 lever, regardless of its external or internal nature or its source from the arms or from the waist, an advanced Taijiquan practitioner should be able to easily handle it. But if you employ a Class-3-lever in a disjointed manner, you will create resistance that will provide an attacker an opportunity to detect your intension.

In constrast, the biotensegrity framework and GRF plus torques resulting from relaxation has the exact opposite effect and allows you to unload the incoming force, maintain your body stabilization, and strengthen a counterattack.

Moreover, when counterattacking, the GRF and torques exerted on the attacker can have a "sticking" effect to induce and then follow the resistance from the attacker for you to take advantage of the situation for counteracting.

Establishing A Biotensegrity Framework for Defensive Actions

There is no denying that countering the attack may expose the body to a powerful force. Whether or not the oncoming force can be received depends on many factors such as the timing and angle of the attack, the execution trajectory, the amount of the force, and the neutralizing skills. If the opponent's oncoming force is powerful and fast, dodging and retreating should be considered by junior practitioners. Defending and controlling the oncoming force by an advanced Taijiquan practitioner depends on a disciplined state of relaxation and the person's force sinking abilities; which together form a tactical tensegrity framework of body integration and equilibrium. In this case, integration means that no one muscle is solely performing just one movement, such as stabilizing one body area for freedom of movement in another body area, but all muscles are working as a combined unit all the time, to reach a stable, but dynamic equilibrium.

Accordingly, if there is an impact on one part of the body, a skilled Taijiquan practitioner will start by following the attacker's strength, so that the impacting force is distributed evenly to the relaxed body as a whole without exposing the center of mass.

In other words, the moment of neuromuscular integration and body equilibrium is to find balance and an ease of motion through oppositional strength; with support of the unison of tensioned and compressed parts of the musculoskeletal system forming biotensegrity.[19] Biotensegrity is the application of tensegrity (the tensional behavior of the body) to biological structures such as muscles, bones, fascia, ligaments and tendons; or rigid and elastic cell membranes; which are made strong by the combined action of tensioned and compressed parts.[20]

During the moment of *Jin* receiving (receiving a blow), the musculoskeletal system maintains tension through a continuous network of muscles and connective tissues, while the bones provide discontinuous compressive support.[21]

To sustain the required elasticity for biotensegrity, the matrix of interconnected soft tissues including fascia, muscles, tendons, and ligaments must maintain the right amount of tension. This can be compared to tree roots forming a structural network that holds tension within the earth. If the body is just slightly out of alignment, or the required tension and compression becomes disorganized (or unbalanced), the discrepancy will prevent optimal motion and function of biotensegrity.

However, when the body is relaxed and rooted downward, gravity is pressing the body structure down into the ground. Then a rebounding GRF and torque (rotational force) along with the kinetic chain momentum reverberates up the body structure. The integrated internal movement of multiple joints and muscles helps reduce the impacts of oncoming attacks within the biotensegrity framework.[22] Subsequently, a fully developed body proprioception and capacity of sensing body motions are recruited to react to the sudden attacks and to self-correct spontaneously and apparently effortlessly.

Proprioception relies on mechanoreceptors located in deep tissues such as muscles, tendons, and fascia sending detailed messages to the brain about body stabilization and movement. It is evident that martial arts training such as Taijiquan can improve the required proprioception and neuromuscular control.[23]

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Cultivating the *Jin* and Recognizing the Qi

What is Taijiquan's *Jin*? Rather than using the general term "internal force", it is defined here as "the integrated GRF and rotational torques launched by the body through a kinetic chain, using mechanically efficient mechanisms."

Thus, any external and/or internal forces applied by a Class-3 lever are excluded, regardless of their external or internal nature, or their sources, which may be from the arms or from the waist. Taijiquan tactics emphasize simultaneous defense and offense, although neutralization takes priority.

The synchronized transition from a defensive action (receiving the *Jin*) to an offensive action (launching the *Jin*) requires both sensing and neutralizing the incoming force, to control the timing and the opportunity before a counteraction. Concurrently, the feet, legs and waist must be fully integrated, in preparation for launching the counteracting *Jin*. The feeling of integration, derived from sinking (also known as rooting), originates not only from having good balance but also from connecting all parts of the body down to the ground.

This corresponds to the Taijiquan Classics: "*When launching the Jin, one must sink and relax completely while aiming at the desired direction* (发劲须沉着松净，专注一方); *and the power accumulated as drawing a bow and released as an arrow* (蓄劲如张弓，发劲如放箭)".[24]

Thus, the resulting *Jin* (GRF and torques) for offense depends on the sensitive neuromusculoskeletal control cultivated by routine diaphragmatic breathing, the degree of relaxation and mindfulness to sense the GRF and various torques, and the efficacy of transferring the GRF and torques throughout the body kinetic chain.

For Taijiquan's closed kinetic chain movement, the *Jin* is the GRF plus the consequential three-dimensional internal-reaction torques of joints, muscles, and ligaments that synergistically thrust all body segments upward from the feet.[13] Here, the *Jin* is equal to the change in momentum over the change in time.

Practicing the traditional Taijiquan through awareness, breathing and movement explorations can help foster kinesthetic sensory cultivation, body consciousness, and internal strength enrichment. While cultivating the Qi routinely through diaphragmatic breathing, the *Jin* will be enhanced over time by integrating body kinetic chain motions, to progressively enhance the neuromusculoskeletal sensitivity. This allows deep-layer core muscles to engage more effectively outside of the inhibiting influence of mobilizing muscles, and thus the kinetic chains can be properly utilized for efficient kinetic energy transfer, from the proximal segments to the distal segments, for launching any *Jin*.[13]

The magnitude of momentum generated by the GRF and torques, and transferred from segment to segment via the kinetic chain, can be sensed, but the kinetic energy as a scalar quantity cannot be felt. To help cultivate the *Jin* during Taijiquan training for martial arts application, it is necessary to scientifically delineate the Qi here as "kinesthetic sensations of position, movement, and force of muscles, tendons, and joints throughout body segments in kinetic chain motions" to help monitor the progressive sensation of the momentum transfer.[13]

Augmenting *Jin* from Ground Using Class-2 Lever

When the lower-body is correctly balanced and the body parts -- particularly the ankles and feet -- are sufficiently relaxed, the gravity sensory feedback from activation of plantar cutaneous mechano-receptors can help manage the torque produced by the forces of gravity and reaction of the ground.[25] The key movements of the ankle joint complex are dorsiflexion/plantarflexion occurring in the sagittal plane, abduction/adduction occurring in the transverse plane, and eversion/inversion occurring in the frontal plane. Rotation in any given plane occurs about an axis perpendicular to that plane. Moreover, the movements of the ankle joint complex are controlled by the torques due to ground reaction. The vertical GRF, horizontal friction forces, and ankle torque at the time of the plantarflexion movement are shown in Figure 3.

DOI: 10.57612/2022.JTS.01.02

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Digital Edition: ISSN 2832- 062X
Print Edition : ISSN 2832-0611

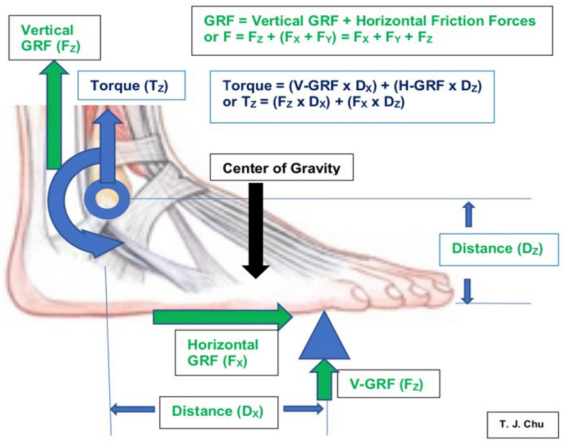

Fig. 3 Diagram showing Ground Reaction Forces (GRFs) during the plantarflexion movement along with the resultant ankle torque (which can be estimated by multiplying the GRF components by their respective perpendicular distances).

The torque can be estimated by multiplying the body weight by the perpendicular distance of the upward effort from the fulcrum (which is also referred to as the pivot point, or center of pressure (CoP)) plus the component resulting from the horizontal friction forces (see Figure 3). In biomechanics, the center of pressure (CoP) is the term given to the point where the GRF vector is applied; whereas the center of gravity (CoG) is the point where the whole weight of the body acts vertically downward. It is important to note that both the CoP and the downward position of the CoG are not static outcome measures because of the dynamic actions of "Five Steps" during the Taijiquan movements.

For example, the CoP is at the ball near the toes at the time of a ward-off or push posture, or it moves backwards to near the heel at the time of a roll-back posture.

Similarly, for the sake of body stability, the downward position of the CoG should be placed at the "bubbling well" (which is a point on the sole of the foot, just in front of the arch and centered side to side) at the time of a ward-off or push posture, or it shifts to below the ankle at the time of a roll-back posture.

More specifically, the "bubbling well" is located one third of the way from the base of the toes to the edge of the heel on the sole of the foot between the metatarsals of the 2nd and 3rd toes.[13]

In plantarflexion of the foot, the lower leg acts as a Class-2 lever. A Class-2 lever (e.g., a wheelbarrow) is the only lever that can guarantee that the effort (input force) arm will always be greater than the load (output force) arm.

This arrangement results in a higher effort-arm to load-arm ratio, making this Class-2 lever the most mechanically advantageous. In a calf raise, the effort comes from the calf muscles (gastrocnemius, soleus, plantaris); which is attached to the calcaneus bone. In this case, the load comes from the body weight, plus any extra weight from an opponent, which acts on the lever system through the tibia. Here, the fulcrum (the pivot point) is made up of the metacarpophalengeal joint. In this arrangement, the load is then in the middle, and the effort is furthest from the fulcrum. Therefore, the act of plantarflexion can move much more weight than elbow flexion. This is even if the bicep is just as strong as the calf.

Both GRF and torques are influenced by contraction of lower leg muscles. Thus, contracting the calf muscles occurs when the fulcrum (CoP) is placed at the ball of the foot and the body weight (a downward of the CoG) is shifted to the "bubbling well" (see Figure 4A), at the time of advancing during the "Five Steps" movements.

Shifting both CoP and CoG forward (towards the toes) can help maximize the vertical GRF and torques by taking advantage of a Class-2 lever system (where the load (CoG) is located between the fulcrum (CoP) and the upward effort). At the time of retreating during the "Five Steps" movements, contracting the shin muscle (tibialis anterior) can occur when both CoP and CoG are shifted backward where the fulcrum (CoP) is placed at the heel and the body weight (CoG) is under the ankle (see Figure 4B). In this case, the advantage of a Class-2 lever system can also apply. Accordingly, the positions of CoG and CoP can be adjusted to maximize the vertical GRF and torques (greater than the body weight) by using the torque of body weight for self-initiated movements or for responses to an external perturbation force. Moving the body weight to exploit the torque of gravity can be performed with great skill, by advanced Taijiquan practitioners.

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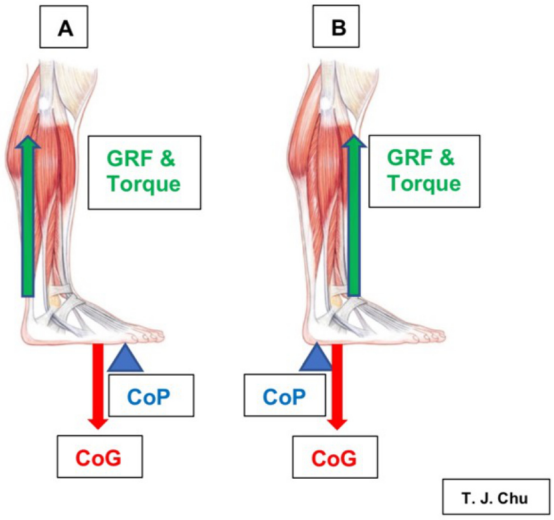


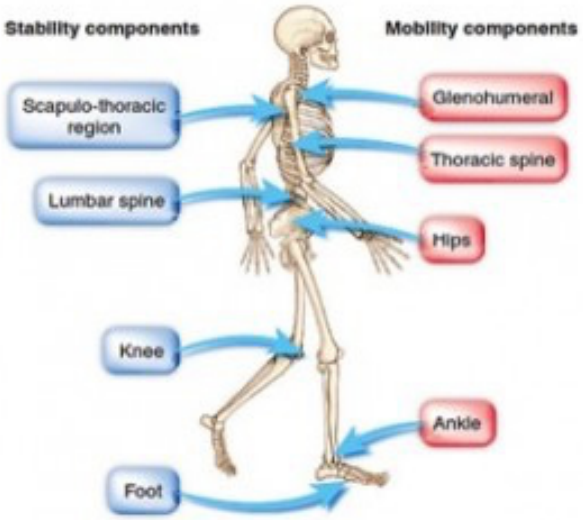
Fig. 4 –Ground Reaction Force (GRF) and torques augmented by Class-2 Lever: (A) GRF and torque increased by contracting the calf s where CoP is at the ball and CoG is placed at the bubbling well; and (B) GRF and torque increased by contracting the shin muscle where CoP is at the heel and CoG is placed below the ankle.

Essentially, the explosive GRF with torque generation is the ability to increase *Jin* (GRF, torques) as quickly as possible during a rapid muscle contraction in the lower legs. The rate of force/torque development during rapid muscle contractions is determined by the capacity to produce maximal voluntary activation in the beginning phase of an explosive contraction.[26] A change in the contraction of the lower leg muscles often precedes the contraction of the upper body muscles. The GRF and torques can be easily transmitted by body-wide muscle coordination activated by nerve potentials to move the joints and limb segments upward.[27] Most skeletal muscles in human body are attached to bones via tendons close to joints, causing these musculoskeletal systems to be Class-3 levers with mechanical advantages less than one (i.e., the input force is greater than the output force.) Advanced Taijiquan practitioners understand that it's easier to perform a weighted calf raise than a bicep curl or a tricep extension, because the lever system involved in a bicep curl or a tricep extension is mechanically less efficient than the lever system involved in a calf raise.

The next stage, to boost the *Jin* upwards, is attributed to the angular torque at the ankle while the GRF vector passes upward from the foot and produces movement at each lower extremity joint, starting from the leg segment to the waist segment.

Biomechanically, the interrelated groups of body segments, connecting joints, and muscles work together to perform movements along with the portion of the spine to which they connect. The concept of a joint-by-joint approach implies that the body is made up of "mobile" joints and "stable" joints that alternate as the body segments moving up starting from the ground such that the mobile joints can gain leverage off the stable joints to effectively transfer the momentum (see Figure 5).[28]

The *Jin* (GRF, torques) is initiated at the proximal leg segment and proceeds to the more distal segments, with the more distal segment initiating its motion at the time of the maximum speed of the proximal segment. Each succeeding segment generates larger endpoint speeds than the proximal segment.[29] Thus,



[Image Courtesy of National Academy of Sports Medicine]

Fig. 5 Transfer of *Jin* (GRF and torques) along with accompanying momentum and kinetic energy occur through four body segments from feet to hands: legs (ankles through knees to hips), waist (hips through pelvis/sacrum/lumbar to thoracic spine), chest (thoracic spine through shoulder blades to shoulder joints), and arms (shoulder joints through elbows to wrists).

DOI: 10.57612/2022.JTS.01.02

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Print Edition : ISSN 2832-0611

the vertical GRF and torques at the feet as aided by the Class-2 lever of the ankle plantarflexion, or dorsiflexion can be further reinforced by the angular torques firstly at the ankles of the leg segment and subsequently at the hips of the waist segment. In fact, each joint torque can produce linear and angular acceleration of all body segments, due to the dynamic coupling inherent in the interconnected musculoskeletal system. Angular acceleration of the waist and chest segments is principally affected by all the joints of the leg segment with varying degrees of dependence during the gait cycle.[30] For instance, when the pelvic rotates at the waist segment in the transverse plane, the other joints of the lower limb are involved in rotation as well. In fact, the greater the joint's distance from the trunk, the greater is the rotation (e.g., the tibial rotation is three times the rotation of the pelvis).[31]

Using Only Mechanically Efficient Mechanisms for Offensive Actions

The human body is composed of a variety of joints; some work biomechanically like levers, others like pulleys, and still others like a wheel-axle mechanism. The synovial joints are moveable and function as lever systems. Most movements in the human body are classified as Class-3 lever systems, which are at a mechanical disadvantage in terms of effort versus load.

In fighting, most of the time, people tend to use unconnected, or unintegrated brute force attack, by using the ends of their limbs. If the physical force is delivered in the arm by moving the hand around the wrist, moving the forearm around the elbow, or moving the whole arm around the shoulder; all these levers are Class-3 type levers with the effort between the resistance (load) and the joint (fulcrum) where the muscle attachments are usually close to the joint. In Taijiquan, the practitioners learn to stabilize those Class-3 levers and integrate them into a tensegrity framework for self-defense under the constant pressure of gravity.

For offense, while letting the tensegrity framework relax, advanced Taijiquan practitioners can develop an excellent way to exert the *Jin*, cleverly using the musculoskeletal system to establish mechanically efficient levers with the GRF and torques rooted in the feet, issued in the legs, dominated by the waist, and delivered to the hands. In other words, using GRF and torques generated from the feet will help convert many inherent Class-3 levers in the human body to either a Class-1 or a Class-2 lever in offense.

The first instance is indicated in the Taijiquan Classics as "*The power comes from the spine* (力由脊发)".[24] In this case, the Taijiquan practitioner can place the fulcrum on the moving axial line (spine) between the GRF with torques (effort) and opponent's body (load) by turning the pelvis around the hip to swing the whole body as a Class-1 lever. It requires very little effort to deliver the *Jin* from the ground toward opponent's center of mass.

The second instance is also indicated in the Taijiquan Classics as "*The force is borrowed from the opponent* (力从人借)".[32] In this second case, the Taijiquan practitioner can place the fulcrum on an opponent's forceful arm with the opponent's body (load) between the fulcrum of the opponent and the GRF with torques (effort) of the practitioner by turning the pelvis around the hip to swing the whole body as a Class-2 lever. This way the Taijiquan practitioner can borrow the incoming force along the direction and momentum of opponent's arm against the opponent's body with little effort because the core power is connected to the torso while applying the GRF with torques toward opponent's center of mass.

Additionally, the Taijiquan Classes indicate that "*Stand like a balance and rotate actively like a wheel* (立如平准，活似车轮)" and "*The Qi is like the wheel, and the waist is like the axle* (气若车轮，腰如车轴)".[32, 24] The rotation of the waist/pelvic region is like turning a wheel on an axle. The hip joints are rotating around the moving axial line (spine) at about the elevation of the sacrum. As is well known, the wheel-and-axle mechanism is able to mechanically aid the movement of very heavy loads. Besides, the muscles around the pelvis have high muscle-to-tendon ratios (force producers) while the extremities have relatively much more tendon and elastic structures (force amplifiers). In a correctly aligned body, a small movement of the waist along with the *Jin* from the

DOI: 10.57612/2022.JTS.01.02

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Digital Edition: ISSN 2832- 062X
Print Edition : ISSN 2832-0611

ground can produce very large amounts of force elsewhere in the body.

The Taijiquan Classics indicate that: "*Use a force of four ounces to deflect a thousand pounds* (牵动四两拨千金)".[33] This is the level that all serious Taijiquan practitioners are keen to attain. The prerequisite of using four ounces to deflect a thousand pounds is the ability of receiving the *Jin* while neutralizing the incoming force by following its direction of movement. To induce the opponent's attacking force to emptiness, the point in contact must naturally rotate and the arc of rotation must be aligned in accordance with the direction of the incoming force. Regardless of the magnitude of a force coming to attack, the impact is zero in its tangential direction at the target point. As a result, only a small amount of friction force is required to achieve the effect of "deflecting a thousand pounds with four ounces of effort". The key lies in sensing the incoming force and inducing the opponent to a tangential direction effortlessly.

Taijiquan is an interesting and effective martial art like playing American football with specific defensive and offensive strategies. In defense, the Taijiquan practitioner is relaxed, forming a stable biotensegrity framework. In offense, the Taijiquan practitioner is efficient and can powerfully use mechanically efficient levers (within a living fulcrum) along with the efficient wheel-and-axle mechanism.

Conclusion

Practicing Taijiquan can be enjoyable, challenging and fulfilling for health benefits; and it should improve the practitioner's skill as a martial artist as well.

However, many people may still wonder how a "soft" Taijiquan can be an effective martial art. Here, the secret may lie in the fact that many Taijiquan's martial aspects have been misunderstood and many physical and psychologic skills may take years to develop if the method employed is inadequate. Moreover, some may be misinformed and do not fully understand the mysterious nature Qi and they may not understand how body mechanics can make their moves more powerful.

This study provides an extensive review of the structure, function, and motion of the biomechanics of Taijiquan and offers a scientific clarification that may help martial art achievement. The mysterious Qi and *Jin* are scientifically defined, to help understand the essence of Taijiquan.

As the fundamental step to develop the martial ability, the lower limbs should have six degrees of freedom to help control the eight types of actions of the upper limbs. To overcome the initial fear of fighting, the routine diaphragmatic breathing can be a powerful tool to take control away from the amygdala hijack. Diaphragmatic breathing can further enhance neuromusculoskeletal control to help maintain the central equilibrium of the body.

In defense during free fighting, the most difficult action is to receive and neutralize the oncoming force. This requires training on relaxation, proprioceptive and interoceptive awareness, as well as the basic skills of touching, sticking, connecting, and following. Additionally, establishing a biotensegrity framework in the body from relaxation and alignment are necessary to help disperse incoming forces for defensive actions.

Synchronizing a quick switch from defense to offense requires a sensitive neuromusculoskeletal control as cultivated by routine diaphragmatic breathing to allow effective transfer of GRF and torques upward throughout the body kinetic chain. The sensational feeling of Qi can help monitor the momentum transfer. The powerful *Jin* (GRF and torques) of Taijiquan is augmented at the feet using a Class-2 lever. The way to apply the augmented *Jin* from the ground naturally and with agility is by reducing the dependence on local muscle strength (avoiding Class-3 levers) and using whole-body power efficiently (enabling Class-1 and Class-2 levers and wheel-and-axle mechanisms).

More research in the topic areas is recommended, and it is clear that new advances in science can empower us with new ways to further comprehend the Taijiquan Classics and help reveal Taijiquan's martial capabilities. It is highly recommended that future research on both the health and martial aspects of

DOI: 10.57612/2022.JTS.01.02

Vol.1 Iss.1 / June / 2022
Digital Edition: ISSN 2832- 062X
Print Edition : ISSN 2832-0611

Taijiquan should recruit those who have acquired certain *Jin* from the ground and can demonstrate Taijiquan's soft-style martial arts. Further scientific research studies on Taijiquan's *Jin* (GRF and torques) are certainly needed, including direct measurement via kinematic data analysis and indirect estimation via computer modeling.

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