

# Starting Strength

## Analyzing the Squat

by

Nicholas Soleyn

*“There is simply no other exercise, and certainly no machine, that produces the level of central nervous system activity, improved balance and coordination, skeletal loading and bone density enhancement, muscular stimulation and growth, connective tissue stress and strength, psychological demand and toughness, and overall systemic conditioning than the correctly performed full squat.”*

—Starting Strength: Basic Barbell Training (3rd Ed.)

Many of us have preached this quote to others, advocating the squat as the fundamental exercise for developing real, full body, functional strength. However, because fear of a thing will always rule the popular opinion, we are continuously wading through poorly reasoned claims that squatting is dangerous, unnecessary, or better if only performed halfway. Unqualified summary assessments like “squats are bad for your knees” are particularly frustrating, because they are thrown around without reference to a standard or model and, consequently, with no analysis of what happens within the body during a “correctly performed full squat.”

Any analysis of a movement or exercise—and any conclusion that it is good, bad, or otherwise—must have as its basis a well-defined, standardized model. The model defines the movement as correct. Potential deviations from the model are not valid bases for analyzing the model itself, because such deviations are, by definition, incorrect. For example, if we argue that the squat is both safe and beneficial for one’s knees, neither an incorrectly performed squat nor variations of the movement may provide a suitable basis for a counter argument or concluding otherwise. As Rip wrote, discussing the press, “you don’t get to redefine the exercise and then claim that it’s dangerous.”

A standardized model must consider all potential body types. Beginning with a mechanical analysis of the levers, angles, and forces of the lifter-barbell system involved in the squat, we must develop a set of circumstances that will hold true for all anthropometries. Once we have established the mechanical model, adding an anatomical analysis is fairly simple. Both are necessary to discuss adequately the squat’s safety, benefit, or value as a fundamental exercise. To illustrate, this discussion focuses on whether the squat is safe and beneficial for the lifter’s knees.

## **Mechanical Analysis: Levers, angles, and forces**

The mechanical analysis of the squat concerns the development of rotational force throughout the range of motion. This force, called moment force, is greater the further the barbell moves, horizontally, from one of the body's joints. That distance is called a moment arm, and the relative lengths of the moment arms affecting each joint show the relative portion of the overall force, for controlling or lifting the barbell, that affect the joints throughout the movement.

### **The Top of the Squat**

At the top of the squat, the lifter is standing in a relatively straight vertical line with the bar on his back. In this and all barbell exercises, the forces acting on the body originate with the force of gravity pulling down on the barbell in a straight vertical line. The bar is held directly over the middle of the foot so that the whole system is considered "in balance." This condition of balance will remain throughout the entire movement.

The levers that exist in this analysis are the back, the femur, and the shank or lower leg. The levers, as they hinge around the hip and knee joints, form the diagnostic angles used to analyze and discuss the movement. These angles are the hip angle, defined as the angle formed by the plane of the torso and the femur; the knee angle, formed by the femur and the shank; and the back angle, formed by the plane of the torso and the floor. At the top of the squat, these angles are completely open, placing the back, thigh, and shank segments at zero degrees to the vertical force of gravity acting on the barbell. There can be no moment arms in this position. The entire kinetic chain—the components of the musculoskeletal system involved in the production and transmission of force between the base of support (the floor in this case) and the barbell—is in compression.

### **On the Descent**

As the lifter begins the descent into the bottom position, the knee and hip angles begin to close and the back angle becomes more horizontal. These angles create moment arms along the back, femur, and shank. The body is descending and these angles are closing. The force generated by the body around these angles is resisting the moment force of the barbell proportionate to the development of their respective moment arms.

### **The Bottom of the Squat**

The bottom of the movement is defined by the apex of the hip angle dropping below the horizontal plane parallel to the knee. The knee, hip, and back angle have all closed further. The hips have been pushed back as the hip and back angle have closed in order to keep the load balanced over the middle of the foot.

The closing angles have created a horizontal displacement of the points of rotation—the hip, knees, and ankles—relative to the vertical gravity vector acting on the barbell. Gravity, acting on the barbell, is transferring force along the body's levers to these points of rotation. The amount of force being transmitted to each of these points is directly proportionate to the length of the moment arms acting on each lever, created by the horizontal displacement of the bar and joints when the lifter closed those angles. Moment arms are measured horizontally between the point of rotation and the vertical gravity vector (from a sagittal view of the lifter, think about a line dropped straight down from the barbell on the back). This shows several moment arms acting on the body's points of rotation.

Two levers and moment arms affect the hip joint. The back lever is the distance from where the bar is carried to the hip, measured along the plane of the torso. The horizontal displacement of these two points creates a moment arm that is equal to the horizontal distance between them. The other lever affecting the hip is along the proximal femur. The gravity vector crosses the femur creating

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a lever segment between this point and the hip joint. This lever segment has a moment arm equal to the horizontal distance between the hip and the gravity vector. The moment forces transmitted along these levers are controlled by the hip and must be overcome for the hip to open from this position.

The other lever segment created from the point at which the gravity vector crosses the femur extends to the distal femur and affects the knee. The moment arm that determines the amount of rotational force transmitted along this lever is measured horizontally between the gravity vector (proximally) and the knee (distally). Given the relatively open knee angle, and a knees-out/knees-back position that effectively shortens the length of this lever segment, the moment arm created and the proportionate moment force transmitted here is small relative to the amount of moment force affecting the hip angle.

The shank is similarly divided into two lever segments and two other moment arms that must be considered. The proximal lever segment exists between the knee and the point at which the gravity vector crosses the shank, and has a moment arm equal to the horizontal distance between the knee and the gravity vector. The distal lever is measured along the shank from where the vector crosses the shank to the ankle, with a moment arm that is measured horizontally between these points. The moment force represented here affects the ankle.

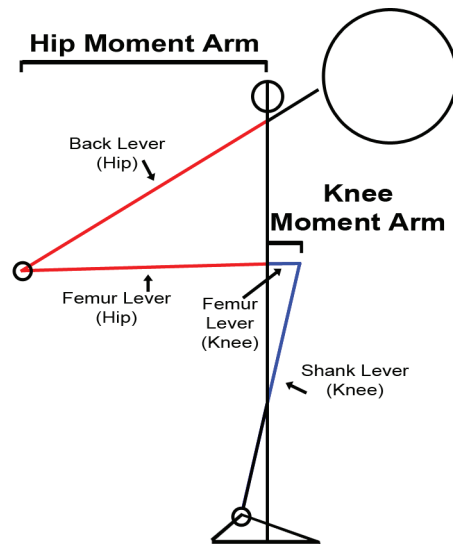
In the correctly performed squat, the barbell is directly over the middle of the foot. There is no moment force affecting this balance point with the ground, and the lifter/barbell system is, therefore, in balance.

Assuming the barbell remains balanced over the mid foot, one can manipulate the moment forces acting on the body through bar placement and the closing or opening of the diagnostic angles. Moment force is directly proportionate to the length of the moment arm in the lever system. The distribution of these levers and the relative lengths of the moment arms affecting the hips, knees, and to a lesser extent the ankles, illustrate the amount of moment force acting on each point of rotation. In the correctly performed full squat, the largest moment arms affect the hip.

### Standing Back Up

To stand back up to the starting position the lifter must generate sufficient moment force at each of the points of rotation to overcome the moment force acting on each point, generated by the force of gravity acting on the load. Each point of rotation is responsible for a percentage share of the total force that must be generated. This share is directly proportionate to the relative length of the moment arms affecting each joint, along its levers.

The squat places the largest distribution of the load on the hip. The levers controlled by the hip are along the back and the proximal femur, and they have the longest moment arms. Variations on



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the squat, such as the front squat or the high-bar squat change the relative length of the moment arms involved. These versions of the squat employ a more vertical back, a more open hip angle, and a more closed knee angle. The effects of these differences are a much shorter moment arms affecting the hip, as the vertical back angle and the open hip angle have brought the hips horizontally closer to the barbell, and larger moment arms affecting the knee as the closed knee angle has caused a more “knees-forward” position, moving the knees horizontally further from the load. These knee dominant variations are not “correct full squats” for purposes of our analysis. In our squat, it is the hips that drive the bar back up.

The finished position is the same as the starting position. The back is vertical and the hip and knee angles are completely open. The moment arms affecting the rotational points would have been gradually shortened to nothing on the way up so that now the entire system along the kinetic chain is, once again, in compression.

## **Anatomical Analysis: Adding bones and muscles**

Having established a basic model based on levers, angles, and moment forces it is necessary to next put the model into the context of the musculoskeletal system. The bones make up the levers, the muscles control them, and the connective tissues tie the whole system together. The squat is a full body exercise, exhibiting loaded human movement through a large range of motion. As opposed to any isolation or single joint exercise it is important to consider the entire system and how it works together through the full range of motion to analyze relatively narrow issues, such as knee health.

### **At The Top**

At the top of the movement, the bar is held on the back, carried just below the spine of the scapulae. The elbows are lifted and the chest is raised so that the bar is resting on the “shelf” of muscle created by the posterior deltoids, just underneath the trapezius muscles and is locked into position by the wrists. The back is held rigid by the spinal erectors in natural thoracic and lumbar extension. The abdominal muscles contract isometrically, and a big held breath further supports the spine. The lifter will maintain the rigid back throughout the movement.

The muscles of the body are generating only enough force to align the skeleton to efficiently resist the compressive force gravity operating on the barbell. The bar is directly over the middle of the foot as measured from the back of the foot, not the shin, to the front of the toes. The hips and knees are fully extended. The lifter’s stance will be about shoulder width apart, and he will point his toes out about thirty degrees.

### **The Eccentric Phase**

The eccentric portion of the movement begins by flexing the knees and hips. The hips are pushed back and the knees travel forward to keep the bar balanced over the middle of the foot. The flexing of the knee and hip angles loads the extensors of those joints eccentrically.

The glutes and hamstrings are the primary hip extensors. The glutes are being loaded eccentrically preparing for hip extension. The hamstrings function should be considered in relation to the position of the pelvis and knees. The hamstrings attach at the bottom of the pelvis, at the ischial tuberosity, which can rotate around the hip joint. The spinal erectors, whose job is to hold the back in rigid lumbar extension, attach to the sacrum at the top of the pelvis. As the hips are pushed back and the back becomes more horizontal, the hamstrings pull on this attachment to the pelvis, which is rotating away. Because the erectors tilt the pelvis forward to keep the back in rigid lumbar extension,

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the hamstrings lengthen proximally. However, the hamstrings also cross the knee joint and are knee flexors. Since the knees are being flexed, the hamstrings are being shortened distally. This simultaneous lengthening and shortening means that the hamstrings do not change length much during this portion of the movement. Therefore, the hamstrings function can be thought of as isometric contraction controlling the hip angle.

The flexing knee under the load eccentrically loads the quadriceps. The quadriceps muscles are the knee extensors attached to the anterior tibia via the patella and the patellar tendon.

Also, as the lifter unlocks his knees, he forces his knees to track out parallel to the toes by externally rotating his femurs. He will keep his knees out, engaging the external rotators of the femurs, so that they track parallel to the direction of the toes until he locks his knees in extension on the way back up. This action not only brings these external rotators into the movement, but also stretches the adductors, loading them eccentrically so that they can contribute to the concentric phase of the squat. The lifter will maintain this toes out/knees out position throughout the movement.

### **The Bottom Position**

Mechanically, we defined the bottom of the squat by the hip dropping below parallel. This position is defined anatomically as the hip joint dropping below parallel with the top of the patella. This is the longest effective range of motion because several things happen in this position.

The hamstrings reach a full stretch. As the hip angle closed, the pelvis tilted forward, lengthening the hamstrings. For the bar to remain over the mid-foot, depth must be a function of hip angle, and the more acute the angle of the hip the more tension gets loaded on the hamstrings. For most people, dropping the hips deeper would require slackening the hamstrings proximally by allowing them to pull the pelvis out of alignment, rounding the lower back. Rounding the back would diminish the hamstrings ability to maintain hip extension; it would decrease the back's efficiency, as a force-transmitting lever, making it less rigid; and it would expose the lower back to injury. In contrast, where the hamstrings have reached a full stretch they are in the best position to contract isometrically and anchor the hip angle. This is a good thing because, as we saw in the mechanical analysis, the hip angle is responsible for the biggest share of force necessary to get out of the bottom of the squat.

The adductors also reach a full stretch just below parallel. Having kept the knees shoved out over the toes, the lifter has eccentrically contracted these muscles, preparing them to contribute to lifting the load. The adductors comprise five muscles that attach along the medial and posterior aspect of the femur, and on the ischium and pubis of the pelvis. On concentric phase of the squat, as the hip angle opens the distance between the medial femur and the medial pelvis shortens, such that the adductors contribute to hip extension.

In addition to bringing the adductors into the movement, the act of shoving the knees out moves the femurs out of the way of the anterior superior iliac spine of the hip (ASIS). If the lifter does not shove the knees out, depth will be cut off prematurely because the femur will become impinged on the ASIS. If the femur is impinged the only way the lifter can get lower is by rounding the back into lumbar flexion, because squat depth is a function of hip angle: if the hip angle cannot become more acute because the femur is mashing all the connective tissues between it and the ASIS, then depth can only come from the posterior tilting of the pelvis and the rounding of the lower back, which is an inefficient and unsafe practice. This range of motion, then, is the longest effective range of motion because it is the deepest position that is both mechanically efficient (all the levers are rigid) and allows the greatest amount of muscle mass to contribute to extending the hips, which is the main drive out of the bottom position.

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### **Concentric Phase: Generating Force**

At this point, the lifter must reverse direction by generating sufficient force with the posterior chain and quadriceps to overcome the moment forces acting on the hip and knee angles originating with the force of gravity on the barbell.

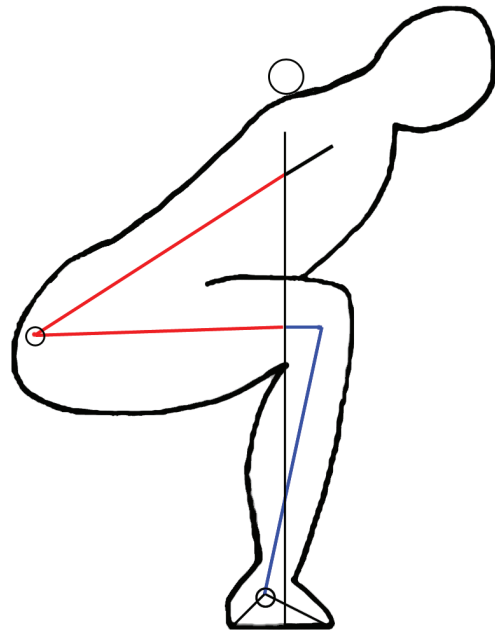
The back is the longest lever in the movement. It remains locked in rigid lumbar and thoracic extension so that the spine serves as an efficient force transmitter. The spinal erectors and the abdominal muscles remain tight in isometric contraction, supported with a big held breath.

The hips must extend from the bottom position. From our mechanical analysis, we know that the greatest proportion of the total force necessary to get up from the bottom position must come from the extending of the hips. The hamstrings, adductors, and glutes transitioning from eccentric to concentric contractions create a slight rebound or “bounce” as the hips are driven up from the bottom position. A tight, stretched muscle contracts harder than a looser, shorter muscle. This stretch reflex occurs because the stretch tells the neuromuscular system that a contraction is about to follow and a more efficient firing of more contractile units always happens when preceded by a stretch. Stretching the hamstrings for this bounce is a key reason the back must remain rigid as the hip angle closes and the back becomes more horizontal. Because of this stretch, the hamstrings generate a large portion of the rebound that begins the extension of the hip. They contract proximally on the hip and distally at their insertion points on the tibia when performing this function.

The knee joint must also extend in this phase of the lift. There are two moment arms affecting this joint: one at the distal femur and one proximally along the tibia. These segments are the levers operated by the knee extensors, the quadriceps. The quadriceps contract and create anterior force that crosses the knee joint from the femur and pulls on the anterior tibia via the patella and the patellar tendon.

Extending the hips and knees, all the muscles in the posterior chain, the adductors, and the quadriceps work to return the lifter to the starting position in which the body is in compression, the load being fully supported by the skeletal system.

Now we have established a model for the squat, which we can use to compare variations, such as the front squat or partial squat, or analyze issues with the squat itself, such as its usefulness as a fundamental exercise or its effect on one’s knees.



### **The Partial Squat**

The issue of knee safety requires a brief contrast between our model and a partial squat, as the partial squat is often offered as a safer alternative to the full squat.

A partial squat is not easily definable as it may be a quarter squat or a half-squat by actual range of motion. No matter the depth, a partial squat will necessarily have some important differences in



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leverage and anatomical functions. First, the partial squat will yield a more vertical back angle at its bottom position. The mechanical result is that the proportionate moment force acting on the hip is very small. The hamstrings and hip extensors are not positioned to contribute much force to lifting the barbell. In particular, the hamstrings have not been stretched proximally because the back has remained vertical. They will not contribute much effort to the hip extension.

The proportion of the load has been shifted to the knee angle. With a more vertical back and relatively knees forward position, there is a much longer moment arm between the gravity vector bisecting the femur, proximally, and the knee joint, distally. The knee extensors, the quadriceps, are the primary muscle group being worked in this position. The net result of this position is that the quadriceps muscles now have a disproportionately large share of the force, generating a much greater anterior force relative to the hamstrings weak posterior force.

## **Safe and Beneficial for the Knees**

Whether something is “safe” is a question of whether the activity is either likely or unlikely to cause injury. Regarding knee safety, the issue is whether the activity is going to stress the joint or its connective tissues in a manner that carries an inherent risk of injury. Perhaps, in the simplest terms, an activity is unsafe if it causes the knee to do something it is not supposed to do.

From its construction, we know that the knee joint and the bones comprised therein are not supposed to do certain things. The knee has ligaments to prevent the forward (anterior) or backward (posterior) movement of the tibia relative to the femur: The anterior cruciate ligament and the posterior cruciate ligament, respectively. The knee suffers medial injuries when there is a lateral side force on the knee while bent, such as happens often in skiing. The knee also is not meant to handle more than slight internal or external rotation. The knee was meant to operate as a hinge joint, more or less protected against rotation.

In a correctly performed full squat, the knee is stabilized by anterior and posterior contractions and is not subject to any potentially injurious rotational force. The knee operates in one plane, as a hinge joint is meant to operate, and the forces controlling knee extension and flexion, the quadriceps and hamstrings, are balanced.

The lifter places the knees, initially, in a position in which no rotation of the femur relative to the tibia occurs. The toes out/knees out position allows the femurs to rotate externally, accommodating back angle and squat depth. This allows the femurs to assume a natural alignment with the tibia. If, for example, one tries to squat with a very wide stance and feet straight forward, the femurs want to rotate externally but are prevented by the ligaments in the knee anchored by the foot against the floor. This alignment produces tightness in the ligaments and knee capsule itself. Where the toes are pointed out to allow the femurs to track out, while keeping them in line with the tibia as in the correct squat, there is no tightness in the knee capsule. The “bounce” out from the bottom position is not due to knee ligament tightness. The bounce is felt due to stretched adductors and hamstrings. The correctly performed squat places very little, if any, tensile stress on the ACL/PCL, because the lifter bounces off of the stretched and tightened components of the posterior chain and the proportionately loaded quadriceps.

The manipulation of moment forces also contributes to knee safety. In a correctly performed squat, the quadriceps are loaded proportionately to their function. The quadriceps create anterior force, pulling forward on the tibia. However, the squat has a “knees back” and “hips back” position relative to other squat variations. This position shifts the greatest portion of the load to the posterior

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chain and stretches and loads the hamstrings to contribute to extending the hips. The hamstrings provide strong posterior force pulling back on the tibia, balancing the anterior force of the quadriceps.

Compare this to a partial squat in which the quadriceps are the primary movers and the hamstrings contribute little to the movement. Necessarily, the hamstrings are not able to balance the anterior force of the quadriceps; the hamstrings can no longer provide the ACL's function. Patellar tendonitis and ACL injuries from unbalanced and shear forces are a potential result. Moreover, even though the partial squat exhibits a very short range of motion, it allows the lifter move much more weight than that which the body, including the knee joint, may have adapted to support.

The squat creates no forces that stress the knee in any manner other than how it is meant to operate. The squat balances the forces acting on the knee so that it is stabilized throughout the movement. The squat is safe for the knees.

Hypothetically, a squat could harm the knees if the load exceeded the lifter's strength. However, such an excessive load, like partial squats, is not the subject of this analysis. Correct squatting also presumes that one is has trained for and adapted to weights that have become increasingly heavy. In no rational way does the analysis of a squat's safety involve dropping an excessively heavy load on an untrained lifter's back and seeing how it will affect his knees. Anyone who is squatting heavy weights has adapted to do so. Which, actually, is why squats are beneficial for the knees.

The squat stresses the knees in exactly the way they are meant to function, causing salutary adaptations of the bones, muscles, and connective tissues that make up the knee joint. Squats intentionally and progressively stress the entire body through a large range of motion for the hips and the knees. The result of this intentional adaptive stress is an increase in bone density and strengthening of the connective tissues and muscles that support the joint. These are all changes that promote long-term knee health.

In addition to these directly beneficial adaptations, the squat provides various other systemic adaptations that are also beneficial. The squat trains the lifter to stabilize the load and his own body in space. As a result, the squat improves central nervous activity, balance, and it trains the energy pathways. These changes reduce the risk of accidental knee injury due to lack of coordination, balance, fatigue, or a lack of basic, full body strength.

The conclusion is the same that has been variously pronounced, stated, and declared by others, but which I will put down again here: In the absence of a prohibitive injury or condition, every person who can squat, should.

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**Nicholas Soleyn, J.D.**, owns a small publishing company in Albuquerque, New Mexico. Through his study of the law, work as an editor for a legal journal, and work as a law clerk for the New Mexico Supreme Court, he discovered a passion for research and writing, which he now pursues full time. His has also trained in and coached amateur boxing, martial arts, and endurance sports. As Starting Strength Coach, Nick brings his analytical approach to strength training, and he is privileged to help people discover their athletic potential through the barbell. [soleynni@gmail.com](mailto:soleynni@gmail.com).

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