# A Step Forward to Normal Knee Kinematics with Single Radius Knee

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With the decreasing trend of average age in patients undergoing total knee arthroplasty (TKA), patients may be expecting more from their TKA than in the past. It has been reported that approximately 20% of TKA patients experience some level of dissatisfaction with their outcome after surgery.[1] Younger patients tend to have a greater need for more range of motion, longer implant stability, decreased anterior knee pain and faster rehabilitation.

Since the first TKA was performed, surgeons have been constantly improving the surgical approach along with implant and instrument design. As surgical techniques have evolved, femoral components are routinely implanted in external rotation to improve collateral ligament isometry and enhance patella tracking.

TKA implant design evolved according to the research performed on knee anatomy and kinematics. In the mid-70s, the J-Curve theory was proposed and drove the first monumental implant development in TKA. In the past, many successful implants were developed concomitantly. However, as our surgical technique has changed, it is important to make sure that our current implant designs match our scientific approach to implantation to provide TKA patients with more natural and stable knees.

With further improvement in research technology, the understanding of relative motion with regards to the tibia and femur, and the crucial role ligaments play in knee kinematics have evolved. New research approaches have led to the single axis theory to better explain the flexion/extension (F/E) motion of the knee joint. This new theory has led to the development of a knee design with a more circular sagittal profile, or the so-called Single Radius (SR) knee geometry. Previous knee designs had pronounced elliptical sagittal profiles as they were based on the Multi-Radius (MR) theory. The objective of this paper is to provide a critical analysis of the MR theory, introduce the science of a SR theory and contrast knee designs based on each of these theories.

## MR or J-Curve Theory

The MR concept was first hypothesized by Braune and Fischer *et al.* in 1891. They believed that the kinematics of the knee occurs about a variable F/E axis that was located in the posterior femoral condyles, and that this axis was perpendicular to the sagittal plane[2]. This theory was also proposed by several other investigators[3–5].

To further investigate the MR theory, Frankel and Burstein *et al.* used a planar mathematical technique called Reuleaux Method to locate the instant canters of rotation in 1971[6]. They acquired 6-8 lateral roentgenograms of each subject's knee from full extension to 90° of flexion. The next step was to locate two reproducible femoral points on each x-ray image (Figure 1 A). The researchers then superimposed the tibial images on two sequential x-rays, for example from 0 to 15 degrees of flexion. The displacement vectors were determined for each of the two anatomic points and from them, the instant centers were calculated based on the Reuleaux method (Figure 1).

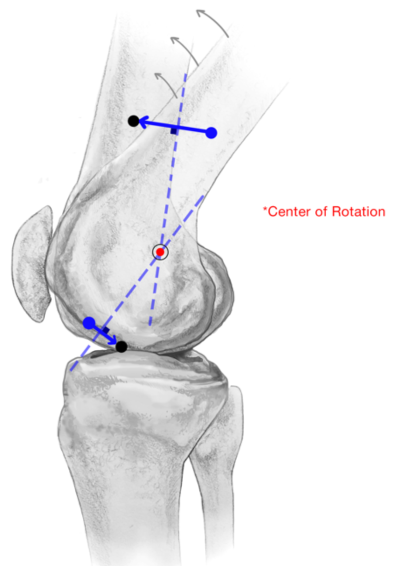


**Figure 1.** The Reuleaux method: (A) The first point was determined by first drawing a line that bisects the femur, then locating the point where the line intersects with the distal femur. The second point was determined by locating a point 10 cm proximal to the first point. (B) The Instant centers of rotation were determined by finding the intersection (the red dot) of the perpendicular bisectors of these displacement vectors (the black arrows) of the two femoral points as the knee went into full extension in this case.

They reported that the instant centers of rotation changed throughout flexion and extension when determined in this fashion. It was postulated that the sagittal profile of the posterior femur formed a “J” shape when the instant centers of rotation were connected (Figure 2).

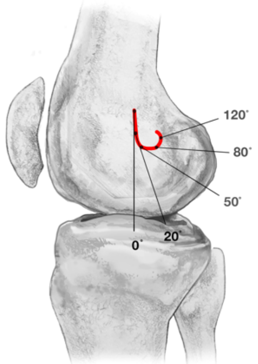


**Figure 2**. The connection of Instant Centers of Rotation form a “J” shape. As the  flatness of a shape is proportional to the length of the radius, this would suggest that the distal condyle is markedly flatter than the posterior condyle- leading to egg shaped designs.

The methodology of the Frankel and Burstein  investigation which was the basis of the MR theory has been criticized by several researchers.[7,8] Some of the criticisms include: 1)  the method used to determine results involved x-rays rather than actual knee motion, and 2) the major flaw was the assumption that all knee motion was occurring in the plane in which the x-rays were taken. Any out of plane motion, such as the obligatory internal/external (I/E) rotation of the tibial during knee flexion, would have adversely impacted the accuracy of the center of rotation calculation.

Meanwhile, results of the other studies conducted using similar methods indicate that the center of rotation analysis is extremely sensitive to experimental design errors. Studies conducted by Blacharski[9], Siegel[10] and Smidt[11] have been criticized by Panjabi *et al*[8] because improper experimental design led to inaccurate results and larger variations (95% confidence interval were calculated to be 2.84cm for Frankel Study and 6.28cm for Smidt study), which makes it difficult to draw conclusions from these studies[7–11].

Another criticism of the Frankel/Burstein study is that they only determined two anatomic points on the femur to locate the instant centers of rotation. When studying the motion of only two points on the femur, the intersection of their perpendicular bisectors will always be a single point. It would have been instructive to have included a third anatomic point femoral point to confirm that its perpendicular bisector would have intersected at the same point.

The largest criticism of the application of the Reuleaux method for studying knee motion is the assumption that the images are capturing all of the knee motion. The accuracy of these displacement vectors used to determine the centers of rotation is adversely affected by any out of plane motion. Clearly, the knee internally and externally rotates with flexion and extension. Consequently, any conclusions based on the application of assumed planar motion to what is clearly nonplanar motion need to be questioned.  However, many contemporary knee designs continue to incorporate a MR design based on these questionable investigations (Figure 3).

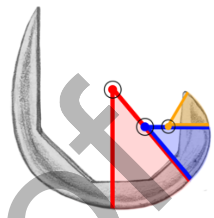

**Figure 3**. To mimic the changing centers of rotation and shape of the femur in sagittal plane, the MR implant typically consists of larger radii distally and smaller radii posteriorly.

## Fixed Flexion Extension Axis Theory

In 1986, Hollister and Kester first reported that the motion of the knee can be described by single F/E axis using a device called the Axis Finder[12].

The axis finder is a simple device to locate the axis of rotation of a rotating body. This mechanical device consisted of a series of metal rods connected via universal joints which permit the positioning of an axial rod to be located along the axis of rotation of two linked segments undergoing a rotation.   As the motion is occurring, the axial rod’s motion will describe an arc unless the axial rod is pointing along the axis of rotation for that motion under study.  It can only be used if the motion under study can be modeled as having a single axis of rotation. Also, if a joint under study has more than one axis, each motion must be studied separately (i.e. the F/E axis must be studied separately than the I/E axis). The documented accuracy of the device when studying a hinge joint is within 1 mm and 1.5°.[7]

Hollister and Kester[7,12] used axis finder on both *in vivo* and *in vitro* specimens to determine the axis of rotation. To study flexion and extension in a cadaver model, the axis finder was attached to the tibia and a Steinman pin (the adjustable axial rod) was freely locatable in the space around femur. The cadaveric femurs were mounted on a specially designed frame. The tibia was passively moved from flexion to extension to locate the axis for this motion. In this study, they reported that:

- The knee has a fixed F/E axis that is in the posterior aspect of the femoral condyles
- The location of the axis is just distal to the origins of the collateral ligaments, and slightly externally rotated with respect to the sagittal plane.
- The tibia has an independent longitudinal rotational axis for internal/external rotation that projects posteromedially from the anterior cruciate ligament (ACL) attachment on the tibia.
- The knee motion has obligatory motion in all three planes due to the offset F/E axis, like the motion in an ankle joint.
- The shape of the femur is circular with larger medial contour when viewed down the axis (Figure 4).

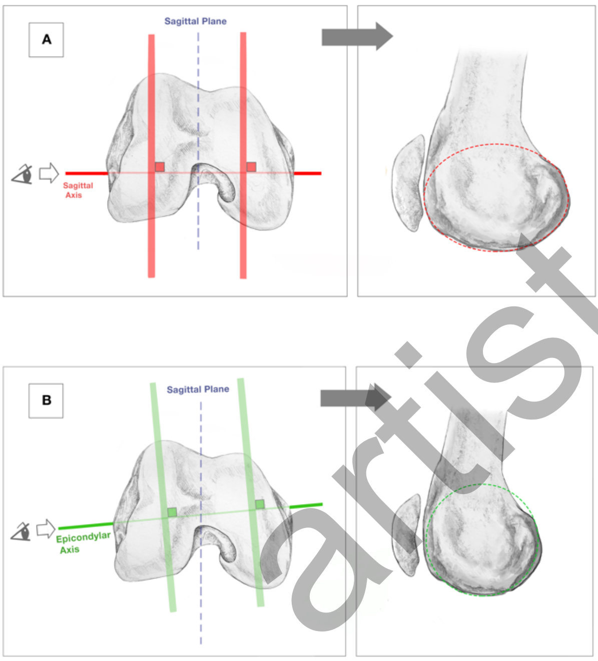


**Figure 4 A&B.** Figure A shows the distal end of the femur. The red line shows the sagittal plane from the MR theory. If the knee is viewed from the side along this J curve axis, the knee has an elliptical shape. In contrast, Figure B shows the SR axis which is coincident with the epicondylar axis. When the knee is viewed down this axis, the profile is circular. This circular profile of the SR knee design is indicated when the femoral bone is resected in external rotation.

This study was one of the first reports documenting the circular as opposed to elliptical femoral condylar shape[6]. In a previous study, Hollister, Kester and Cook *et al.* had used the axis finder and reported the condyles appeared to be circular but could not document that the circularity was present in full extension[12]. Based on the findings of the previous study, Hollister *et al*. further investigated the concept using the same method in 1993 and concluded that the knee axis from the previous study was valid through full extension[7].

After these studies, additional research groups have focused on studying knee motion and the location of the functional F/E axis. In 2005, Asano *et al*.[13] conducted an *in vivo* study using a computer assisted biplanar image matching technique. The objective was test the hypothesis that the knee has a fixed F/E axis in the posterior femoral condyles and this axis coincides with the epicondylar axis. The investigation used a weight bearing squatting activity to study this hypothesis. The findings showed a fixed oblique F/E axis and its location which supported the circular contour of the femoral condyle determined in the previous study by Kester and Hollister.[7,12]

Freeman *et al.* further investigated the arcs of knee motion with radiographic imaging, magnetic resonance imaging (MRI) and autoptic methods, and believed that there are 3 distinct arcs of motion: hyperextension, active flexion and hyperflexion. Fundamental active flexion arc, where the everyday activities occur, ranges from ~30° to 110°. Through the active flexion arc, both femoral condyle surfaces are circular in profile[14 15].

Churchill, Incavo, Johnson *et al*[22] tested the hypothesis that all knee motion could be described in terms of rotations about two axes- a F/E axis and I/E rotational axis. They used a validated test fixture in which 15 cadaveric legs went through simulated squatting activity. The motion was captured with electronic sensors and optimal axes were calculated. The F/E axis was found to be coincident with the epicondylar axis, and the I/E rotational axis was fixed to the medial tibial plateau. During a squat, all knee motion could be described as rotation about these two fixed axes, except for an average 3.4mm in translation and 2.9°in orientation. This research strongly supported the work by Kester and Hollister.[7,12]

Coughlin *et al.* used ten whole cadaveric knees with electromagnetic sensors and recorded the position of the patella relative to the femoral bony coordinate system and found out that the position and motion of the patella relative to the femur was a circular shape. This indicated that the shape of the femoral contour was circular and also uncovered an important relationship between the F/E axis orientation and the arc of patellar tracking[16].

Howell *et al.* studied 155 varus knees and forty-four valgus knees using MRI scans that were obtained perpendicular to the F/E axis of the femur and reported that the femoral condyles are circular when viewed down this axis[17].

These six different research groups using different research methods produced similar results. This further underscores the accuracy of the conclusions of Kester and Hollister regarding both the circular shape of the condyles and the location of the axes of rotation.

Just as the advent of J-Curve theory brought multiple radius implants, the advent of Fixed F/E Axis theory also led to a new type of implant design - a SR design - availln the 1990's, Mark Kester worked with Stryker Corp. and developed the first generation of SR knee implants. The designs were based on the goal of replicating the SR geometry based upon viewing the condyles along the functional F/E axis. Surgeons have evolved the way that they set femoral component in TKA. Femoral components are set in slight external rotation. This was done to improve patella femoral tracking and achieve better collateral ligament balancing by setting the component in line with functional F/E axis[7,12,13,18–22]. The design reinforces the benefit of the common surgical approach of externally rotating the femoral component by implanting a circular, not elliptical, femoral component whose geometry better matches the bone being resected when the cuts are externally rotated (Figure 5). Egg shaped implants based on the application of the Reuleaux method cannot convey this benefit.

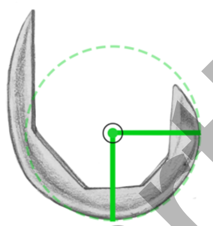

**Figure 5.** SR implants maintain a consistent geometry throughout the functional range of motion, This consistent geometry leads to more consistent soft tissue tension

The center of the circular shape of the SR implant (the rotational axis of the implant) is in line with the functional F/E axis. Consequently, the design of the implant is in agreement with the most common surgical procedure of TK involving the external rotation of the femoral component[18-21]. Therefore, SR implants may be more capable of reproducing normal knee kinematics after surgery, as reported by Churchill *et al*[22]. and Kessler *et al*.[23]

Externally rotating the femoral component, however, raises a concern if implanting a MR femoral component. It is necessary to question the clinical consequences produces by implanting an egg-shaped implant when the resected bone is circular in geometry. Multi radius implant design are not based on an externally rotated view of the femur and consequently, they may not convey the same clinical benefits when implanted in external rotation as a SR knee design.

## Theoretical Advantages of Fixed Flexion Axis Theory in Implant Design

Since the first application of fixed oblique axis theory in implant design in 1996, numerous clinical studies have been conducted comparing SR and MR knee systems. These studies have demonstrated that there are several theoretical advantages of SR design, including more stable mid-flexion, larger range of motion, less anterior knee pain and faster rehabilitation.

### Stability in Mid-Flexion

Stability in mid-flexion is of crucial importance, because it directly impacts patients' postoperative quality of life by giving them confidence in their knee while performing daily activities comfortably, or even independently.

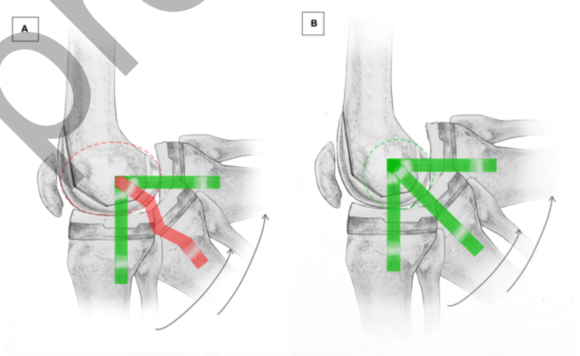


**Figure 6**. (A) In a MR design, when the knee flexes from the distal radii to posterior radii, the ligament tension can change-especially in mid-flexion due to the changing profile (B) Due to the constant geometry of SR implants, the ligament tension remains more isometric, providing the patient with more consistent support.

Various authors have documented that mid-flexion stability is negatively affected when a MR knee design transitions between different radii.24–27 Wang et al. suggested that this instability is caused because the tension of the collateral ligaments changes, resulting in more abduction motion needed to stabilize the knee joint (Figure 6 A)26.,27. Wang et al. also pointed out that it is difficult to correctly adjust the tension of the collateral ligaments throughout the range of motion due to varying radii of rotation in a MR design27. Clary et al. and Gomaa & Williams demonstrated that this instability can produce paradoxical anterior translation of the femur in mid-flexion, which is caused by sudden radial changes when the implant moves from the distal radius onto the posterior radius24,25. Wang et al. observed that the hamstrings of MR patients were co-activated in order to augment knee joint stability.27This co-activation was not observed in patients who received SR knees.

The consistent curvature of SR designs reduces the negative effect caused by the transition of different radii of MR designs by providing smooth articulation surface geometry through the entire range of motion (Figure 6B). In the active flexion range, the SR geometry facilitates intraoperative ligament balancing and provides more varus/valgus stability. Removing instant radius changes eliminates sudden decreases in conformity, which helps reduce paradoxical anterior shift while providing more stability in mid-flexion in combination with ligament balancing[23,26,27].

### Quadriceps Muscle Efficiency

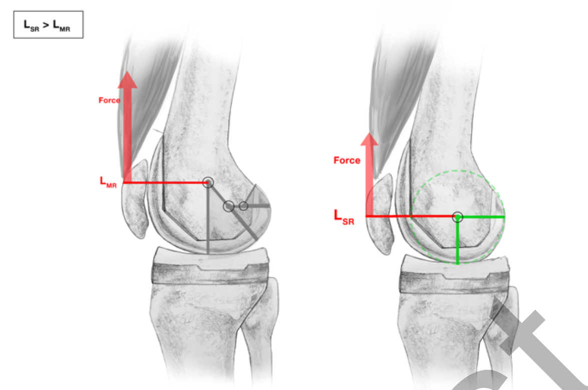


**Figure 7.** A SR femoral design positions the flexion-extension axis more posteriorly when compared to a MR design. This more posterior position increases the length of the patella-femoral moment arm for the SR design. The longer lever arm results in the quadriceps muscle needing to generate less force to reach needed torque levels for patients to achieve full extension. This can benefit patients as their muscles are often atrophied.

The center of rotation in SR designs is placed relatively posterior compared to MR knees. A greater F/E axis lengthens the quadriceps moment or lever arm, which improves the mechanical efficiency of the muscles. D'Lima *et al.* showed that the moment arm in SR design is approximately 1 cm longer than MR designs[28]. Due to this effect, it decreases the quadriceps muscle force needed to attain full extension and reduces joint reaction force.[28] This same effect can also lead to reduced levels of anterior knee pain. In other studies:

- D'Lima *et al.* measured knee kinematics and quadriceps forces using 6 cadaver knees and found that the SR design had a mean 5%-20% reduction in quadriceps tension. The difference was significant at flexion angles greater than 50 degrees[28].
- Ostermeier *et al.* used a device that simulates an isokinetic extension cycle of the knee. Using 12 cadaveric knees (6 physiological knees, 3 SR knees and 3 MR knees), they investigated the amount of quadriceps muscle force needed to extend the knee. The results documented that SR knees had lower quadriceps forces needed to achieve knee extension when compared to the MR knee design tested. [29]
- Mahoney *et al.* observed that after 2 year follow -up of 184 knees (83 MR and 101 SR), patients with the SR knee design showed improved post-operative extensor mechanism function[31].
- Wang *et al.*[26,27] reported that patients who received SR TKA took less time to perform sit-to-stand and stand-to-sit time perhaps due to the higher torque produced by the Sr design. They further demonstrated that patients with MR knees had to increase the effort of their contralateral limb to compensate for their weak TKA limb.
- Gómez-Barrena *et al.* enrolled 60 patients (30 SR and 30 MR) to study postoperative rehabilitation and quadriceps efficiency. They used an Isokinetic Dynamometer to perform isokinetic evaluation, and showed that patients with SR knee had better quadriceps performance and exhibited a quicker recovery in rehabilitation.[30]

### Anterior Knee Pain and Rehabilitation

The extended moment arm and reduced joint reaction force on the patella may lead to reduced anterior knee pain[31,32]. In the Mahoney *et al.* study, it was documented that patients with SR knees had less anterior knee pain compared to patients with MR knees (1% in SR knee patients and 22% in MR knee patients, p=0.001)[31]. Browne *et al.* also demonstrated that reduced patellofemoral forces decreases contact stress between the patella and femur after TKA, which may result in decreased wear and, consequently, longer survivorship[32]. It has also been reported that improved quadriceps muscle efficiency and decreased anterior knee pain results in less effort and more comfort for SR knee patients performing daily activities, such as walking, rising from a chair, climbing stairs and using assistive walking devices, compared to MR knees. Thus, the implantation of SR knees can result in faster rehabilitation[28,32].

These theoretical advantages have proven to be clinically significant by other researchers, as well[30,33,34]. Cook *et al.* compared 426 SR TKA patients with 133 MR TKAs with an average of 3.9 years follow-up. The SR patients had statistically significantly less anterior knee pain (p=0.021), less mid-flexion stability (P=.002), and greater extensor mechanism efficiency, as demonstrated in the patient's ability to fully extend the leg (p=0.025) and climb stairs (p=0.0001). The SR patients also demonstrated faster rehabilitation, as evidenced by improved walking (p=0.0005), improved use of assistive walking devices (p=0.0005) and higher knee society scores (p=0.002)[34].

## Conclusions

There are many factors which can influence a patient's outcome, such as their expectations, surgical technique, rehabilitation, as well as implant choice and design. The SR design is an evolution of knee implants based on multiple research groups employing different scientific methods, yet still arriving at similar conclusions. Knee motion can accurately be modeled as simple rotations about a F/E axis fixed to the femur, and an I/E axis fixed to the tibia. In both the laboratory and clinical setting, the SR design has consistently demonstrated the ability to convey improved biomechanical advantages when directly compared to MR knee designs. These SR benefits include enhanced stability, better patella-femoral mechanics resulting in less anterior knee pain, which ultimately leads to improved patient rehabilitation[24-34]. Implant design is one of the central pillars of successfully treating patients who undergo TKA, and scientific evidence has shown that the SR knee design is a step forward in the goal of optimizing patient outcomes after TKA.

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