HE WANG
A Biomechanical Analysis of the Single-Radius and Multi-Radius Total Knee Arthroplasty Systems for the Sit-to-Stand and Stand-to-Sit
(Under the direction of KATHY J. SIMPSON)

The purpose of the study was to investigate the effect of the design differences between the multi-radius (M-RAD) total knee arthroplasty (TKA) and the single-radius (S-RAD) TKA systems on the functional performance for the sit-to-stand and stand-to-sit movements.

Sixteen participants with unilateral posterior stabilized TKA (8 M-RAD and 8 S-RAD) were involved in the study. Three dimensional kinematic and EMG analysis of the sit-to-stand and stand-to-sit tasks were conducted. One-way ANOVA analyses were performed ($\alpha = 0.05$).

Compared to the S-RAD group, for the sit-to-stand movement, the M-RAD group exhibited greater movement time, trunk flexion, and a tendency for trunk flexion velocity. The M-RAD TKA limb had a tendency for a briefly distinct abduction (ABD) movement during trunk flexion and a greater adduction (ADD) displacement during knee extension as compared to the S-RAD group. Also, the M-RAD group displayed higher TKA knee flexor and extensor activations than the S-RAD group. For the stand-to-sit, the M-RAD group exhibited greater ABD displacement with the ABD peak occurring at a significantly later time in comparison to the S-RAD group. In addition, the M-RAD TKA limb demonstrated greater knee flexor and extensor activations than the S-RAD TKA limb.

As expected, the S-RAD group performed differently from the M-RAD group. The S-RAD group used less effort to accomplish sit-to-stand and stand-to-sit by showing less movement time and knee extensor activation. However, the M-RAD group exhibited compensatory adaptations during the trunk flexion of the sit-to-stand. The greater knee extensor EMG revealed the fact that the M-RAD group had difficulty in performing the sit-to-stand and stand-to-sit movements. Furthermore, the S-RAD TKA knee was more stable than the M-RAD TKA knee during the sit-to-stand and stand-to-sit tasks because the S-RAD TKA knee displayed less ABD/ADD displacement and knee flexor co-activation EMG. The multi radii design might account for the

instability of the M-RAD TKA knee as the short radii used in the mid knee flexion could cause collateral ligaments to lose tension.

In conclusion, the S-RAD TKA design has advantages to facilitate knee extension movements and maintain adequate collateral ligaments' tension.

INDEX WORDS: Total knee arthroplasty, sit-to-stand, stand-to-sit, Kinematic, Electromyography

A BIOMECHANICAL ANALYSIS OF THE SINGLE-RADIUS AND MULTI-RADIUS TOTAL KNEE ARTHROPLASTY SYSTEMS FOR THE SIT-TO-STAND AND STAND-TO-SIT

by

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B.MED., Chengdu Institute of Physical Culture, China, 1994

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A Dissertation Submitted to the Graduate Faculty

of The University of Georgia in Partial Fulfillment

of the

Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2002

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August 2002

ACKNOWLEDGMENTS

I would like to express my sincere appreciation to my advisor Dr. Kathy Simpson for her guidance and encouragement through my academic journey at UGA. I would like to thank my committee members: Drs. Baumgartner, Ferrara, Mahoney, Olejnik for their advice and support throughout this research project. I would like to thank the Graduate School at UGA for assistance through my Ph.D. program. I would like to thank Stryker-Howmedica-Osteonics Inc. and Athens Orthopedic Clinic Foundation for the financial support in this project.

I would like to thank my fellow graduate and undergraduate students: Samatchai Chamnongkich, Charlie Kim, Destin Hill, and Nate Sanders for their help in collecting and processing data. I would also like to thank my family and my friends for their support and encouragement in completing my doctorate. Finally, I would like to thank God for making all these things possible.

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CHAPTER 1

INTRODUCTION

Artificial joint replacement is one of the major surgical advances of the 20th century. Since the 1950s, total knee arthroplasty (TKA) has become the standard method to treat late stage osteoarthritis and rheumatoid arthritis of the knee joint (Riley et al., 1983). As of 1997, there was an estimated 600,000 TKA operations per year in the world, and approximately 210,000 of these knee replacements were performed in the United States. For 1994 alone, costs exceeded $5 billion in the United States (Freund et al., 1997). As shown in Figure 1.1, the most common TKA consists of a metal femoral component of a bi-condylar shape, a polyethylene component to replace the tibial articular surface and a metal baseplate to anchor this plastic component into the tibia.

The primary purpose of a TKA is to restore normal knee function. Therefore, ideally, a TKA should: (a) maintain the natural leverage of the knee joint muscles to ensure generating adequate knee muscle moments to accomplish daily tasks such as rising from a chair or climbing stairs; (b) allow the same range of motion as an intact knee; and (c) provide adequate knee joint stability. A secondary purpose for a TKA is to last as long as possible without further surgical intervention. Thus, the components of a TKA should not loosen, wear out prematurely, or release polyethylene particles into the knee joint that can cause pain to intact tissues. To accomplish these purposes, it is assumed that the mechanics of an arthroplasty knee should be as similar as possible to those of an intact knee when feasible. Therefore, to allow typical knee motions and mechanics, an appropriate TKA design should replicate the locations of the normal knee's axes of rotation. However, for normal knee movement, the exact locations of the axes of rotation are not uniformly agreed upon.

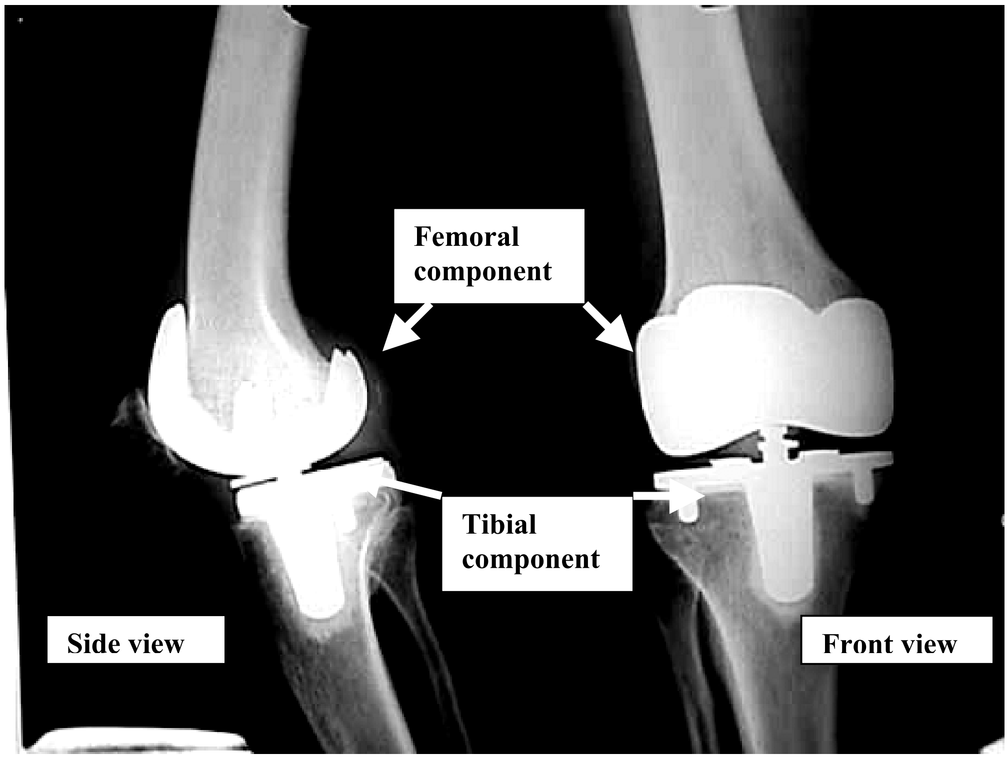

Figure 1.1. Radiographs of a typical TKA of the right limb. The polyethylene tibial insert is not shown.

There are two major theories about the locations of axes of knee motion. First, there is the classic theory, in which it's believed that the knee joint has several instantaneous centers of rotation (ICR) during knee flexion (FLEX) and extension (EXT) (Fick et al., 1911), therefore, the FLEX/EXT axis shifts constantly. An ICR is the point that represents where an axis perpendicularly intersects a plane, in this case, where the FLEX/EXT axis intersects the sagittal plane. Frankel et al. (1971) using sagittal plane radiographs, measured FLEX/EXT ICRs for static knee positions. From 90° of flexion to full extension (0°), the pathway of the ICR locations was semicircular and located in the femoral condyle. Hence, most current TKA designs are based on these results. Consequently, a traditional TKA is designed so that the FLEX/EXT axis shifts from location (Point P1, Figure 1.2a) to at least one other ICR location (P2) during knee flexion/extension.

The second theory regarding the location of the knee FLEX/EXT axis is based on the premise that there is only one location for the FLEX/EXT axis, but the FLEX/EXT axis is fixed to the femur (Hollister et al., 1993; Churchill et al., 1998). Hence, if the femur internally (INTN) or externally (EXTN) rotates, the FLEX/EXT axis is also rotates, and no longer aligned perpendicular to an externally-fixed sagittal plane. Hollister, et al. argued that the classic ICR theory was based on studies in which the results (Fick et al., 1911; Frankel et al., 1971) were obtained from sagittal plane radiographs in which it was assumed that FLEX/EXT axis was always directed perpendicular to the sagittal plane. Therefore, the investigators of these studies misinterpreted the effects of the longitudinal rotation of the femur or tibia as evidence of multiple FLEX/EXT ICRs. By using a multi-dimensional axis finder on cadaver limbs, Hollister et al. (1993) found that there was a single fixed FLEX/EXT axis and this axis passed through the origins of the collateral ligaments. Moreover, they determined that the FLEX/EXT axis passed postero-inferiorly from the medial to the lateral femoral condyle. Two other studies also are consistent with these findings. Churchill et al. (1998) suggested that the optimal FLEX/EXT axis corresponded with the trans-epicondylar line (Figure 1.3). Based on analysis of MRIs of

a) b)

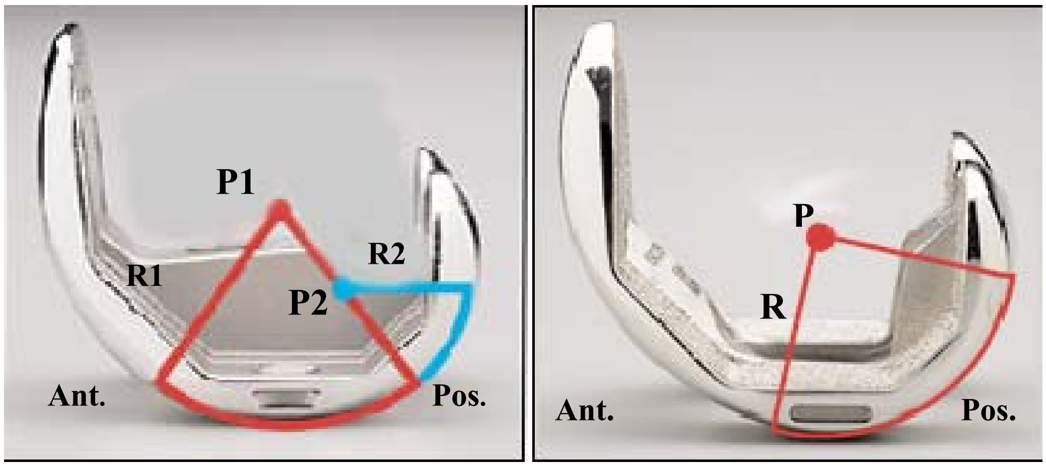

Figure 1.2. Lateral views of left knee femoral components of the a) M-RAD TKA and b) S-RAD TKA. P1, P2, and P represent the centers of flexion/extension rotation, and R1, R2, and R represent the corresponding radii of rotation. (Courtesy of Stryker-Howmedica-Osteonics Inc.)

cadaveric knees, Pinskerova et al. (1999) also confirmed that a single FLEX/EXT axis existed in the knee joint. It was reported that the posterior portion of the femoral condyle was circular in shape (Figure 1.4), hence the knee has only one center of rotation, thus only one FLEX/EXT axis.

Currently, to our knowledge, the vast majority of TKA designs are based on the multi-ICR model and only one design is based on the premise of a single FLEX/EXT axis of rotation. The Scorpio™ (Howmedica-Osteonics, Inc.) has a single radius in the femoral component that corresponds to a fixed FLEX/EXT axis of rotation (Figure 1.2b) and that matches the epicondylar axis shown in Figure 1.3 (Churchill et al., 1998).

Therefore, there are two major biomechanical considerations when comparing a traditional TKA with multiple FLEX/EXT axes and radii (M-RAD) to a TKA with a single FLEX/EXT axis and radius (S-RAD). The first is concerned with the quadriceps and hamstrings moment arm for producing knee extension and flexion moments, respectively, (a muscle moment arm is defined as the shortest distance from the center of rotation to the line of action of the muscle force). As the FLEX/EXT centers of rotation of the M-RAD TKA are more anterior than that of the S-RAD TKA (www.osteonics.com), it is likely that the quadriceps moment arm of the M-RAD TKA is shorter than the moment arm of the S-RAD TKA throughout the range of knee flexion. Consequently, to produce a given magnitude of knee extensor muscle moment, the S-RAD TKA would require less knee extensor muscle force than the M-RAD TKA.

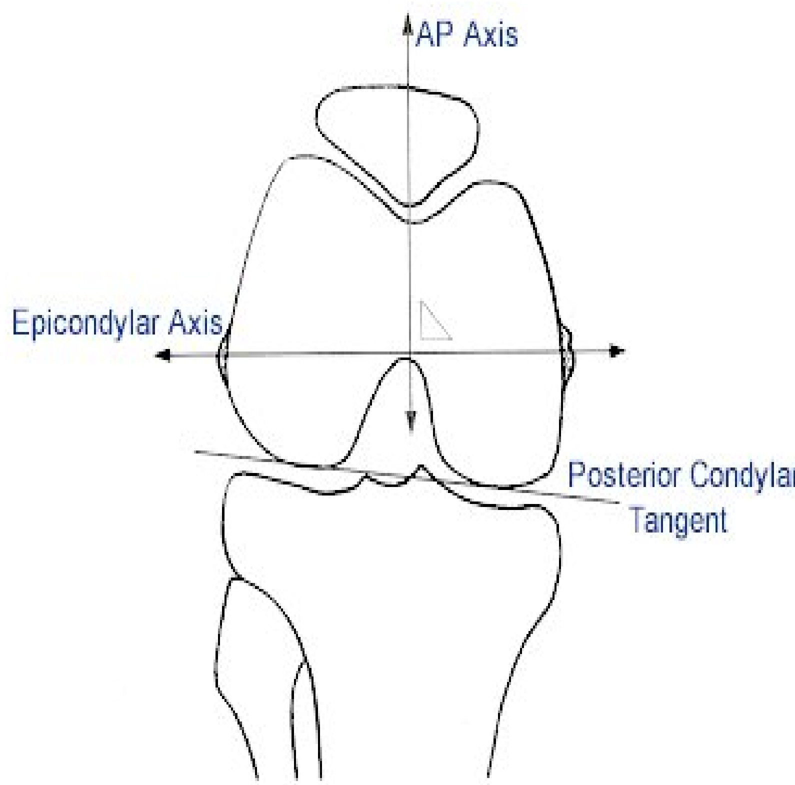

Figure 1.3. Anterior view of knee region of the right leg, including the inferior surface of the distal femur, and the knee joint flexion/extension (epicondylar) and antero-posterior (AP) axes. Churchill et al. (1998) suggested that the optimal flexion/extension axis corresponded with the trans-epicondylar line. The posterior condyle tangent line is used to demonstrate the alignment of the epicondylar axis relative to a line tangent to the posterior surfaces of the femoral condyles.

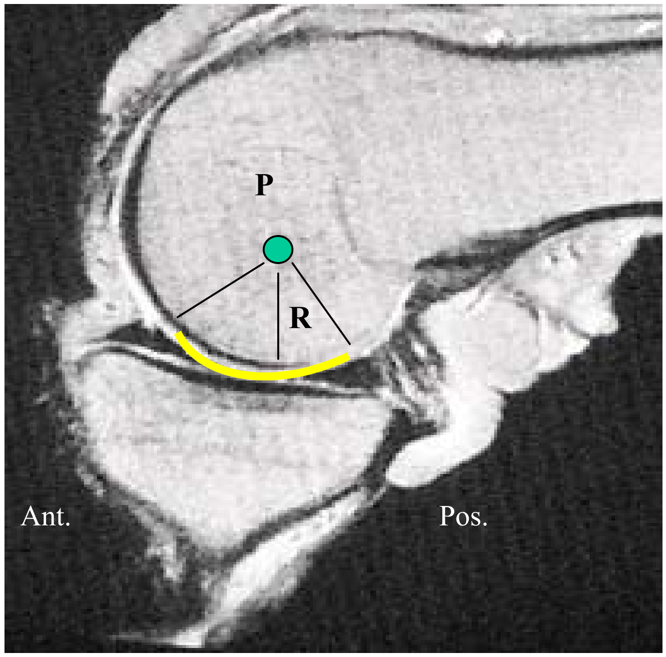

Figure 1.4. Sagittal view MRI of the knee region (from Pinskerova, 1999). Pinskerova (1999) observed that the sagittal plane shape of the posterior femoral condyles were circular, with the center of the circle at P (corresponds with the FLEX/EXT center of rotation) and a radius of rotation of length R.

The second consideration concerns the differences in stability between the two TKA types during FLEX/EXT movement. With at least two FLEX/EXT axes located in the femur, an M-RAD TKA will exhibit a sudden change of radius length when the FLEX/EXT axis shifts from the current radius to the next one. For the S-7000™ (Howmedica-Osteonics, Inc.) and P.F.C™ (Johnson & Johnson, Inc.), the M-RAD TKAs used in this study, the shift from the first FLEX/EXT axis to the second FLEX/EXT axis usually occurs between 30° and 45° of knee flexion (www.osteonics.com) from an extended (0°) position. As the M-RAD TKA knee flexes, the FLEX/EXT axis will shift from P1, which has a longer radius of rotation (R1) to P2, which has a shorter radius of rotation (R2) (Figure1.2a). Theoretically, this transition from R1 to R2 reduces the distance from the femoral attachments of the collateral ligaments to the tibio-femoral contact point (Figure 1.5). Consequently, collateral ligament tension also may decrease, thereby creating the mid-flexion instability at the knee joint that is often reported by M-RAD patients (Mahoney, 1999). Because the fixed FLEX/EXT axis of the S-RAD TKA results in a fixed radius of rotation (R in Figure 1.2b) throughout the range of knee motion, it is reasonable to expect that the collateral ligaments of the S-RAD TKA should better maintain adequate tension throughout the entire range of motion (Figure 1.5) than those of the M-RAD TKA.

Purpose of the Study

The differences in the number of axes and their locations between the M-RAD and the S-RAD TKAs are thought to affect muscle moment arms and collateral ligament tension. However, it is not known if these differences in the TKA designs will cause functional differences between M-RAD and S-RAD participants during activities of daily living, e.g., standing up and sitting down. Therefore, the differences between the unilateral S-RAD and M-RAD TKA participants for knee muscle electrical activity and lower extremity kinematic characteristics during the sit-to-stand and the stand-to-sit movements will be investigated in this Study.

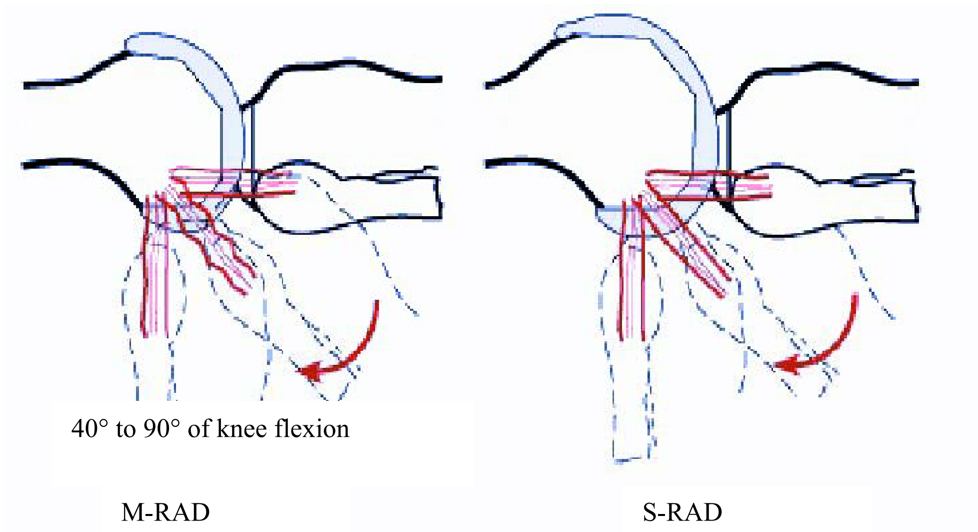

Figure 1.5. Surmised collateral ligament lengths of an M-RAD and an S-RAD TKAs during knee flexion (taken from www.osteonics.com)

Significance of the Study

It has been estimated that by the year 2030 there will be approximately 454,000 total knee replacement procedures annually (www.aaos.org). This is more than twice that reported for 1997 by Freund et al. (1997). As the demand for TKA surgery increases dramatically in the next 30 years, the issues of selecting the right TKA type for patients and evaluating functional performance of the TKA limb become more significant.

Numerous studies (Kelman et al., 1989; Berger et al., 1998; el Nahass et al., 1991; Schlepckow et al., 1992; Ishii et al., 1998; Stiehl et al., 1995; Kuster et al., 2002; D'Lima et al., 2001; Stiehl et al., 2001) have been conducted to investigate the knee strength and TKA knee motion after TKA surgery. Very few studies analyze the knee muscle electrical activity patterns. It is not clear if the EMG technology is an effective way to qualitatively evaluate the outcome of TKA surgery. Although in one of the recent studies, Wang et al. (2000) examined the quadriceps co-contraction EMG during isokinetic strength tests on individuals with a unilateral S-RAD TKA limb, it was found that the S-RAD TKA limb had less co-contraction quadriceps EMG than the Non-TKA(N-TKA) limb. The conformity of the TKA design between the femoral component and tibial component might explain this finding. However, in this study, as only one participant's EMG data were available, further study is required to confirm this finding. Therefore, it is not certain that the S-RAD TKA would reveal different knee muscle activation patterns from the M-RAD TKA.

Moreover, it has been reported that patients with an M-RAD TKA sometimes complain about some varus/valgus (VAR/VAL) instability of their TKA knee (Mahoney, 1999), particularly in the mid-flexion range (45°-70°) when the radius of rotation is abruptly decreased (from R1 to R2, Figure 1.2a). Clients report a reluctance to perform activities for fear of the M-RAD TKA limb collapsing. Therefore, it is important to know if the single radius design of the S-RAD TKA attenuates this phenomenon of mid-flexion instability during knee FLEX/EXT motion during a common daily movement.

Additionally, very little is known about the 3D kinematic and knee muscle activities associated with an S-RAD TKA (Scorpio^{TM}) during knee FLEX/EXT movements because the S-RAD TKA has only been available in the market since 1996. Consequently, it is not clear that during activities of daily living, the S-RAD TKA knee acts more like a normal knee than the M-RAD TKA knee. Furthermore, information is also lacking about the in-vivo 3D kinematic characteristics of the S-7000^{TM} and P.F.C^{TM} (M-RAD) TKA limbs during activities of daily living.

Rising from a seated position, i.e., the sit-to-stand movement, was selected as one of the movements of the study because it is a common daily activity that requires more knee flexion and knee extension moment than level walking or stair climbing (Berger et al., 1998). A number of studies (Yoshida et al., 1983; Burdett et al., 1985; Alexander et al., 1991; Pai et al.,1983; Lundin et al., 1995; Kerr et al., 1997; Yu et al., 2000) have been conducted to investigate the biomechanical characteristics of the sit-to-stand movements. Some studies focused on the influence of age on the sit-to-stand movement (Wheeler et al., 1985; Alexander et al., 1991; Kerr et al., 1997). Other studies focused on the influence of chair height on performance of rising movement (Burdett et al., 1985; Itokazu et al., 1998; Su et al., 1998). However, only a few studies focused on the biomechanical characteristics of the sit-to-stand movement of TKA patients. Su et al.(1998) studied TKA patients' biomechanics of chair rising. They reported that the hip joint and knee joint reached the maximal flexion angle at the end of forward leaning phase. They also found that TKA patients took longer time to rise than normal elderly subjects. In their study, TKA patients leaned more forward during rising than normal subjects. Su et al. (1998) explained that by leaning the trunk more forward, the TKA patients could place the center of mass (CoM) above the knee as well as anterior to the hip and ankle. Therefore, the flexion angle, reaction force and flexion moment of the TKA knee could be decreased. Also, they found that the unilateral TKA patients tended to shift CoM to the non-surgical limb during rising. Itokazu et al. (1998) studied the influence of the chair height on TKA patients. The researchers concluded that a higher chair was more suitable for TKA patients because it required less knee flexion. The authors also suggested that a minimum of 100° of knee flexion was desired for a TKA knee.

Sitting down (a.k.a. the stand-to-sit movement) is an important common daily activity. After reviewing the literature, only a few studies focusing on the sitting down movement (kralj et al., 1990; Kerr et al., 1997). However, very little is known about the TKA design on the functional performance of the stand-to-sit. Although sitting down is a seemingly reversed movement of standing up, the movement contributions that it requires from the trunk, thigh, and shank segments are different from the sit-to-stand. Furthermore, the knee extensor and flexor activate differently during stand-to-sit compared to sit-to-stand. e.g. the quadriceps contract eccentrically to provide enough knee extension torque in order to decelerate the descending motion during stand-to-sit. In addition, the ability to balance the body posture and maintain the stabilization of the knee joints is important when descending the body without hand assistance.

Premises of the Study

The specific premises underlying the hypotheses will focus on the following two areas: knee strength and mid-flexion instability.

Premises on Knee Strength

As discussed earlier, the axis of FLEX/EXT rotation of the S-RAD TKA is more posterior than those of M-RAD TKA (www.osteonics.com). Given the same quadriceps muscle force, with a longer quadriceps moment arm, an S-RAD TKA should promote the generation of greater knee extension torque than the M-RAD TKA.

The sit-to-stand movement is believed to be a kinematicly symmetrical movement (Jevsevar et al., 1993; Itokazu et al., 1998; Yu et al., 2000), in which each leg will attempt to produce a similar amount of the knee extension moment to raise the body. Therefore, In order to produce a similar magnitude of knee extension muscle moment of the N-TKA limb, the M-RAD TKA limb is surmised to generate greater quadriceps muscle force compared to the N-TKA limb and the S-RAD TKA limb. Consequently, we anticipate that the quadriceps of the M-RAD TKA group will have a greater level of normalized RMS EMG activity than that of the S-RAD TKA group during the sit-to-stand movement. As the weakness of the extensor mechanism associated with the M-RAD limbs, we expected that the M-RAD group would take longer time to stand up than the S-RAD group. Furthermore, two compensatory maneuvers required trunk motion (Su et al., 1998) might be used by the M-RAD group for the sit-to-stand movement due to the weakness of the M-RAD limb. First, by increasing the trunk flexion angle, the center of mass (Com) of the upper body could be placed close to the knee joints horizontally. Thus the knee flexion torque generated by the upper body weight is reduced. Second, by increasing the trunk flexion velocity, the horizontal momentum is increased. This horizontal momentum can be transfer into vertical momentum and facilitate the knee extension. Therefore, we expected to see that the M-RAD group would have more trunk flexion and greater trunk flexion velocity that the S-RAD group would during the sit-to-stand movement.

The stand-to-sit movement is seemingly a reversed motion of the sit-to-stand movement. Instead of concentric contraction, the quadriceps eccentrically contracts to decelerate the downward movement. In order to produce similar amount of knee extension torque to the N-TKA knee to counteract the flexion torque generated by the upper body weight, the quadriceps of the M-RAD limb needs to generate more force, thus, more quadriceps eccentric EMG than the S-RAD limbs and N-TKA limbs due to the shorter quadriceps moment arm.

<u>Premises Regarding the Mid-Flexion Instability</u>

In general, for an M-RAD TKA individual, during knee FLEX/EXT motions, after a given degree of knee FLEX/EXT displacement, the axis of knee rotation switches location from the current location to the next location that also changes the length of the radius of rotation, it is suggested that the collateral ligaments will exhibit an abrupt change in tension when, the radius of rotation moves from a longer to a shorter radius of rotation. Consequently, mid-flexion instability may occur due to the temporary slack of the collateral ligaments. However, the S-RAD TKA limb may have reduced mid-flexion instability due to a single radius of rotation that allows the collateral ligaments to remain under tension throughout the range of knee motion (www.osteonics.com). Therefore, for the sit-to-stand and stand-to-sit tests, if the M-RAD TKA limb is affected by mid flexion instability in the particular range from 45° to 70° of knee flexion, we expect that the M-RAD TKA knee will display greater abduction/adduction (ABD/ADD) angles within this range of knee angles than the S-RAD TKA knee during the sit-to-stand and stand-to-sit movement.

Furthermore, the co-contraction of hamstring muscles plays an important role to substitute cruciate ligaments to reduce the shear force during knee FLEX/EXT movement (Kasman et al., 1998). The posterior stabilized (PS) TKA (will be used in this study) limb does not have cruciate ligament. The function of the cruciate ligaments will be replaced by the conformity and post and cam design of the TKA and the co-contraction of the knee muscles. Therefore, we anticipate that the co-contraction normalized RMS EMG of the TKA limb will be greater than the N-TKA limb.

Moreover, the co-contraction of hamstring knee muscles could increase the compressive force between femur and tibia. As the compressive force increases, the dynamical friction between the tibia and femur will increase. Therefore, in order to counteract the instability in the medio-lateral direction due to the slack collateral ligaments in the knee flexion range of 45° to 75°, the M-RAD TKA limb might increase the co-contraction level of the hamstring and quadriceps muscles during FLEX/EXT movement. Thus, we anticipate that the level of co-contraction RMS EMG of the hamstring muscles of the M-RAD TKA group will be greater than those of the S-RAD TKA group in the particular knee flexion range of 45°-75° during the sit-to-stand and stand-to-sit movements.

Hypotheses

The S-RAD group compared to the M-RAD TKA group would demonstrate:

Hypothesis # 1: Less movement time during the sit-to-stand and stand-to-sit.

Hypothesis # 2: Less trunk flexion angle during the sit-to-stand.

Hypothesis # 3: Less trunk flexion angular velocity during the sit-to-stand.

The S-RAD TKA limb compared to the M-RAD TKA limb would demonstrate:

Hypothesis # 4: Less normalized quadriceps and hamstrings RMS EMG for the sit-to-stand and stand-to-sit.

Hypothesis # 5: Less ABD/ADD angular displacement for the range between 75º and 45º of knee flexion during the sit-to-stand and stand-to-sit.

CHAPTER 2

REVIEW OF LITERATURE

This literature review chapter consists five major parts. The first part is a description of the basic anatomy of the knee, particularly the ligaments and muscles. In the second part, the biomechanical characteristics of the kinematics and kinetics of the knee joint motion are presented. Electromyography (EMG) studies reflecting knee muscle activity during activities of daily living are also included. The third part is focused on concepts related to total knee arthroplasty (TKA). The fourth part is related to the biomechanics of sit-to-stand movement and factors influencing the mechanics of performing the sit-to-stand. The mechanics of the sit-to-stand as performed by individuals who have had a TKA also is described. The last part is the literature review of the stand-to-sit movement.

Normal Knee Anatomy

The knee joint is the largest and most complex joint in the human body. It has three compartments, the lateral tibio-femoral compartment, medial tibio-femoral compartment and femoro-patellar compartment. Compartments are separated from each other by connective tissue.

Major Ligaments

Ligaments are connective tissue structures connecting bones. The function of ligaments is to guide joint motion and stabilize joints. The knee joint has four major ligaments, the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), medial collateral ligament (MCL), and lateral collateral ligament (LCL).

The ACL attaches its origin posteriorly on the lateral wall of the intercondylar femoral notch. It inserts into the anterior tibial intercondyloid fossa, which is lateral and posterior to the medial meniscus and lateral tibia spine (Wilson, 1993). Girgis et al. (1975) reported that the average ACL length was approximately 38 mm, and the width was about 10 mm. The PCL has a femoral attachment at the medial wall of the intercondylar notch. The PCL inserts its fiber into the tibia plateau, where the attachment is about 1 to 3 cm below the join line (Wilson, 1993). Girgis et al. (1975) reported an average length of 38 mm and an average width of 13 mm in the PCL.

The MCL has superficial and deep portions. The MCL attaches its origin at the posterior aspect of the medial femoral condyle. The superficial MCL inserts its fiber into the metaphyseal region of the tibia. However, the tibial insertion of the deep portion of the MCL is different from the superficial portion of the MCL. The deep MCL fibers are inserted directly into the edge of tibia plateau and meniscus (Wilson, 1993). Just as its name indicates, the LCL is located at the lateral side of knee joint. The origin is the lateral femoral epicondyle and the insertion at the head of fibula (Wilson, 1993).

Menisci are attached to the margins of the tibia and are interposed between the femoral condyles and the tibia plateaus. The medial meniscus is about 3.5 cm long and is C-shaped, where the lateral meniscus is circular-shape (Wilson, 1993).

Functions of Major Ligaments and Menisci

The ACL is the primary static stabilizer against anterior translation of the tibia on the femur and accounts for about 86 % of the total resisting force to anterior drawer motion (Hsieh et al., 1976; Hughston et al., 1976a; Hughston et al., 1980b). The PCL is the primary static stabilizer of the knee; it provides 95% of the total constraint to posterior displacement of the tibia relative to the femur. The MCL provides the primary restraint to valgus stress of the knee joint. The LCL primarily restrains varus movement and internal rotation of the knee (Wilson, 1993). The most significant function of menisci is to share a great responsibility in load bearing across the knee joint (Wilson, 1993).

Major Muscles of the Knee Joint

Two major muscle groups around the knee joint are knee extensors and knee flexors. The quadriceps is the primary knee extensor muscle group, and it consists of four muscles (rectus femoris (RF), vastus lateralis (VL), vastus intermedius (VI), and vastus medialis (VM)). While the other knee extensors are monoarticular muslces, the RF is a biarticular muscle. Table 2.1 shows the insertions and function of quadriceps muscle group.

All quadriceps muscles apply force on the tibia and, in general, extend the knee joint. When the hip is in a flexion position, the muscle length of RF get shortened, therefore, the RF becomes ineffective as an extensor of the knee (Thompson, 1989).

The hamstring muscle group contains the major knee flexor muscles and it includes the biceps femoris, semitendinosus and semimembranosus muscles. All of these muscles share the same origin on the ischial tuberosity. The semimembranosus and semitendinosus insert on the medial tibial condyle, and the biceps femoris inserts on the lateral tibial condyle and the head of the fibula (Thompson, 1989).

The gastrocnemius muscle is a biarticular muscle that also can assist in flexing the knee. It originates from the posterior surfaces of the two condyles of the femur and inserts on the posterior surface of the calcaneus. In addition to the soleus, the primary plantar flexor muscle, the gastrocnemius also is responsible for the plantar flexion of the foot. The gastrocnemius muscle is more effective as a knee flexor when the foot is in a plantar flexion position. If the knee joint is held in an extension position, then the gastrocnemius will act effectively as a plantar flexor (Thompson, 1989).

Table 2.1. Insertions and functions of quadriceps (Thompson, 1989).

Name	Origin	Insertion	Function
VM	Whole length of linear aspera and the internal condyloid ridge of the femur	Medial half of the superior border of the patella	Extending the knee while the hip is flexed
VI	Upper two thirds of the anterior surface of the femur	Upper border of the patella and patellar ligament to the tibial tuberosity	Extending the knee while the hip is flexed
VL	Outer surface of the femur below the greater trochanter and upper half of the linear aspera	Outer half of the upper border of the patella and patellar ligament to the tibial tuberosity	Extending the knee while the hip is flexed
RF	Anterior-inferior spine of the iliac	Top of the patella and patellar ligament to the tibial tuberosity	Flexion of the hip, and extension of the knee

Biomechanics of the Knee

Knee Movements

The knee region is a complex structure. It consisit-to-stand of two separate joints, the tibio-femoral joint and the patello-femoral joint (Unless otherwise indicated, the term “knee joint” refers to the tibio-femoral joint in this document). Although the major functions of the knee joint are flexion and extension, the knee joint also allows some amount of internal/external rotations (INT_R/EXT_R) and varus/valgus (VAR/VAL). In addition, there are limited antero-posterior and medio-lateral translations.

The axes of flexion and extension.

The range of motion of the knee joint from full extension (0°) to full flexion is approximately 140° (Rasch et al., 1989). The classic theory of the location(s) of the FLEX/EXT (FLEX/EXT) axes stated that there were changing instantaneous centers of rotation (ICR) in the femoral condyle whose path formed a ‘C’ shape. Reuleaux (1876) described a technique (Rouleaux method) to determine ICR of the knee joint. As this technique requires the use of a sagittal plane radiograph of the knee joint, it was assumes that the plane for knee FLEX/EXT remained fixed as the motions about other axes could be neglected. Two identifiable landmark points on the moving segment (e.g., the femur) were chosen and marked on the radiograph. As the segment moved relative to the other segment, e.g., the tibia, the landmarks moved to new positions and were marked. Then, for each landmark, the two marked positions were connected by a line. Then, a second line was drawn that bisected the first at a perpendicular angle. Last, the intersection of the two perpendicular lines was noted to be the ICR. Frankel et al. (Frankel et al., 1971) used the Rouleaux method to define the pathway of the ICR while the knee moved from flexion (90°) to full extension (0°). They found the pathway to be semicircular and located in the femoral condyle. This study established the classic theory of knee motion that continues to be accepted in its original form by some people (Zatsiorsky, 1998)

Hollister et al. (1993) argued that the theory that stated multiple ICR existed during knee FLEX/EXT was not correct. They indicated that it was not accurate to analyze the knee FLEX/EXT movement from a fixed sagittal plane without considering other axial rotations. To determine the number and locations of ICRs, They used an axis finder and MRI methodology to locate a FLEX/EXT axis of the knee. From their experiment, they found that there was only one fixed knee FLEX/EXT axis, which directed from anterio-superior on the medial side to posterio-inferior on the lateral side. The FLEX/EXT axis past through the origins of the medial and lateral collateral ligaments and superior to the crossing point of the cruciate ligaments. The MRI images perpendicular to the FLEX/EXT axis revealed that the posterior portion of the femoral condyles was circular shaped with only one radius of curvature for a given condyle, further suggesting only one axis of rotation. However the radius of curvature of lateral condyle was smaller than that of medial condyle, which would suggest that knee joint rotation about a longitudinal axis also occurs simultaneously with FLEX/EXT, thereby, confirming that the single FLEX/EXT axis moves, not that multiple FLEX/EXT axes exist.

The shape of the femoral condyles has been confirmed by others (Elias et al., 1990; Kurosawa et al., 1985; O'Connor et al., 1989). The posterior aspect of the medial condyle had an average radius of 22.8 mm in Hollister et al.'s study, which was similar to the data from the study of Elias et al. (Elias et al., 1990), who found that the radius of the circular-shaped posterior femoral condyle was about 21 mm. Moreover, some previous studies (Kurosawa et al., 1985; O'Connor et al., 1989) showed that the shapes of the distal and posterior portions of the femoral condyle were spheres. The center of the sphere was the center of the circle formed by the antero-posterior border of the femur as seen in the lateral, sagittal plane roentgenograms.

Internal and external rotation of the tibia.

Internal and external rotation of the tibia relative to the femur is an important part of a healthy knee motion (Wilson, 1993). When the femur is fixed and the tibia is free to move, as the tibia moves from a flexed to an extended position, the tibia externally rotates. The converse occurs during tibial flexion. This phenomenon is well known as “screw-home” mechanism. The anatomical configuration between femur and tibia may result to the tibial external rotation during knee flexion. Smillie (1962) noted that the existence of a larger area of bearing surface on the medial condyle than on the lateral condyle. Smillie (1962) explained that during knee extension, when the whole articular surface of the lateral condyle had been used up, the femur rotated around the tibial spine until the joint was screwed home. Nordin et al. (1980) suggested that the screw-home mechanism provided stability to the joint at any knee position. Zarins et al (1983) found the total amount of tibial INT_R/EXT_R rotation relative to the femur was about 72° to 74° when the tibia moved passively. The tibia had a constant 45° external rotation when the knee was passively extended from 90° to 150°. When the tibia was flexed, the tibia internally rotated 25°.

The cadaveric study of Shaw et al. (1974) showed that the axis of the tibial INT_R/EXT_R rotation passed through the medial intercondylar tubercle of the tibia plateau. Hollister et al. (1993) used an axis finder to locate the longitudinal axis of the tibia for tibial INT_R/EXT_R rotation. They found the axis was fixed in the tibia and passed near the anterior cruciate insertion on the tibia and was directed posterio-medially near the posterior cruciate insertion on the femur. Therefore, the axis was anterior and non-perpendicular to the knee joint FLEX/EXT axis. Hollister et al. (1995) explained that because of the offset between the knee FLEX/EXT axis and INT_R/EXT_R rotation axis, the tibia would present valgus and external rotation during knee extension.

<u>Antero-posterior movement and femoral rollback.</u>

There are some controversies about antero-posterior (A/P) movement of the femoral condyles relative to the tibial plateau. Kapendji (1970) considered that there was a sliding motion accompanied by some degree of rolling between the femoral and tibial surface during knee flexion and extension. Segal et al. (1983) further confirmed that the pure rolling motion occurred during the initial knee flexion and the pure sliding occurred during the final knee flexion. Particularly, when the knee flexed, the femoral condyle moved posteriorly relative to the tibia, this posterior motion of the femoral condyle was called “femoral rollback”. From 0° to 90° of knee flexion, the femoral rollback was about 14 mm (Stiehl et al., 1997).

However, some researchers (Hollister et al., 1993; Pinskerova, 1999; Todo et al., 1999) do not agree with the previous description of the A/P movement of the knee joint. Hollister et al. (1993) found that there was only one fixed axis during knee flexion and extension. This finding suggests that the femoral rollback does not exist because there is no antero-posterior translation between femur and tibia if the FLEX/EXT axis is fixed. In support of this view, Todo et al. (1999) found approximately 2 mm femoral posterior displacement during knee flexion in their MRI study. The findings of Pinskerova et al. (1999) are consistent with those of Hollister et al. (1993). Based on MRIs of cadavers, the posterior femoral condyles were circular shape. Therefore, the center of the femoral condyles where the FLEX/EXT axis past through does not change during the knee FLEX/EXT movement. In addition, Pinskerova et al. (1999) explained that during knee flexion, when the tibia fixed, the femur rotated externally around a longitudinal axis that passed through the medial compartment of the knee. Therefore the observation in sagittal plane revealed the femoral rollback phenomenon.

In summary, the femoral rollback is the sagittal observation of the motion of the lateral femoral condyle relative to the tibia. However, the A/P movement of the knee might not exist when the INT_R/EXT_R rotation of the tibia or femur is taken consideration.

Kinetic Characteristics of the Knee

This following paragraph will summarize the knee joint loading of healthy knee during variant activities. Tibio-femoral force and patello-femoral forces are two major knee joint loadings.

Tibio-femoral force can be decomposed into axial compression force and shear force. Nisell (1985) reported that the tibio-femoral compression force could reach 1100 N (from 30° to 120°

flexion) to 1230 N (at full extension) during knee extension movement with a resistance torque of 40 Nm. With the same resistance torque, the tibio-femoral shear force reached posterior 200 N at 120° of flexion and anterior 600 N in extension. The shear force direction would change according to the pulling direction of the patellar tendon on the tibia. At near extension, patellar tendon pulled the tibia forward and created a positive shear force. However, at flexion position, patellar tendon pulled the tibia backward and changed the shear force direction into negative (van Eijden et al., 1985). Simpson et al. (1997) calculated the tibio-femoral axial loading during single jump dance movement and found the maximum value could reach 16.8 body weight (BW).

Nisell et al. (1985) demonstrated that the patello-femoral compressive force was approximates 0.5 to 1.5 BW in walking; 3 to 4 BW in climbing and 7 to 8 BW in the squat movement. Simpson et al. (1997) studied the patello-femoral force during traveling dance jump, they found as the jumping distance increased the patella-femoral force increased and ranged from 1.8 BW to 15.8 BW.

<u>Joint Stabilization Mechanism</u>

As we discussed earlier, the knee joint received remarkable amount of loading during walking or running. The stabilization mechanisms of the knee joint are important to provide. In order to prevent injury, the knee must be stabilized during movement. There are four primary mechanisms to stabilize the knee joint. A) Passive resistance via increased congruity of articular structure (articular surface of the tibia and femur). B) Passive resistance of connective tissues (ligaments cross the knee joint and the knee joint capsule). C) Passive resistance of musculo-connective structures (tendons and muscle fibers). D) Active resistance from muscle contraction. In the following, we will discuss the passive resistance of connective tissues and active resistance from muscle contraction.

Ligaments are the primary static constrains of the passive joint motion (Wilson, 1993). With a maximum tensile strength of approximately 1725 ± 200 N. The ACL resists most of the anterior shear force on the tibia relative to the femur (Noyes et al., 1984). During an anterior drawer test, 85.1 ± 1.9% of the total resistance force is from the ACL (Butler et al., 1980). With a 90° knee angle, the ACL also limits both internal and external rotation of tibia relative to the femur during extension and flexion, respectively. The PCL is the primary static restraint of the posterior shear of the tibia relative to the femur. The tension in the PCL increases with increased knee flexion and reaches maximal tautness at full flexion (Wilson, 1993). Therefore, the PCL can provide 94.3 ± 2.2% of the total force to restrain posterior translation at 90° of flexion and 30° of flexion (Butler et al., 1980).

The medial collateral ligament (MCL) provides the primary restraint to knee valgus movement (Wilson, 1993). Seering et al. (1980) found that the MCL could provide more than 80% of the resistive force to valgus force. Grood et al. (1981) reported that the superficial part of the MCL provided 57.4 ± 3.5% of total valgus restraint at 5° of flexion and 78.2 ± 3.7% of restraint at 25° of flexion. Conversely, the lateral collateral ligament (LCL) has been observed to be the primary restraint to varus forces at all degrees of flexion (Grood et al., 1981). At 5° of flexion, the LCL contributed 54.8 ± 3.8% of the total restraint force and 69.2 ± 5.4% as the knee moved to 25° of flexion.

The knee ligaments provide the majority passive resistance force to stabilize the knee joint. During dynamic movement, the knee muscle groups provide the primary active resistant force to stabilize the knee joint. There are reports (Markolf et al., 1978; Pope et al., 1979) that muscle co-activation can assist the ligaments to provide knee joint stability during knee flexion and extension movements.

Solomonow et al. (1987) proposed that an ACL-hamstrings reflex arc might serve to improve dynamic stability in healthy knee. The ACL possessed the neuroanatomy needed (mechanoreceptors, e.g. Ruffini endings and Pacinian Corpuscles) to initiate the reflex arc (Schutte et al., 1987; Zimny et al., 1986). When the ACL loads become sufficiently high, the hamstrings are synergistically excited so as to reduce the strains on the ACL (Solomonow et al., 1987). Hamstring co-activation level varied between 17% and 32% of the agonist hamstring maximum effect at the same angle interval (Snow et al., 1993). The hamstring muscle can effectively control the anterior shear force on the tibia at the range of motion 25° to 85° of knee flexion (O'Connor, 1993).

The quadriceps was observed to produce upward force to pull the tibia toward the femur that increased the joint contact forces but provided minimal assistance to the PCL in controlling posterior shear force on tibia (Snow et al., 1995). Compared to hamstring co-activation level, quadriceps co-activation level was significantly less. The quadriceps co-activation level ranged from 5% to 8% of the maximum agonist quadriceps EMG level (Snow et al., 1995).

<u>Muscle Activities of Healthy Knee during Isokinetic Movement</u>

The characteristics of EMG activity of knee muscles have been investigated by several researchers (Baratta et al., 1988; Brownstein et al., 1985; Ghori et al., 1995). There are several interesting findings. (a) During isokinetic test, the left vastus lateralis (VL) and right VL reveal similar amount of mean iEMG (Ghori et al., 1995). (b) The mean iEMG of VL does not exhibit any significant differences between the concentric and eccentric movements from 80° to 20° of knee flexion at 30°/s (Ghori et al., 1995). (c) During isometric test, the EMG activity of the vastus medialis (VM) decreases with the decrease of knee flexion angle (Nakamura et al., 1983; Knight et al., 1979). Similarly, Brownstein et al. (1985) reported that the vastus medialis oblique (VMO) EMG activity is less active in the extended position (for men < 30°, for women < 40°). This finding does not support Thompson’s (1989) statement that the VM can extend the knee joint forcefully in the 10° to 20° of knee flexion.

The role of muscle co-activation is believed to dynamically stabilize the joint (Baratta et al., 1988; Kellis et al., 1996; Solomonow et al., 1987). Baratta, et al (1988) studied the antagonist muscle activity of the knee joint during isokinetic test. They found that the EMG of an antagonist muscle was inversely related to the muscle's moment arm length over the entire range of motion (0°-90° of flexion). They concluded that co-activation of the antagonist was necessary to assist the ligaments to maintain joint stability.

Furthermore, Kellis et al., (1996) reported that the concentric co-contraction EMG was greater than eccentric co-contraction EMG and the order of the co-contraction iEMG level for the four major knee muscles (VM, VL, RF, and BF) was VM, VL, RF, and BF.

In addition, normalization method can influence the co-activation EMG values. In Kellis et al. (1996) study, two different normalization methods were used. One normalization method was called the "static" method; the antagonist EMG values were normalized relative to the EMG of the same muscle demonstrated during a maximal isometric contraction (static). The other normalization method was called "dynamic"; the antagonist EMG value was expressed as a percentage of the EMG activity of the same muscle measured at the same angle interval and test velocity. Compared to the static normalization method, the dynamic normalization iEMG was greater at the initial and final stages of the range of motion (ROM). They concluded that the dynamic method was more appropriate for the determination of the antagonist iEMG patterns during isokinetic movements because it considered factors such as muscle action, muscle length and angular velocity.

Isokinetic Strength

Since the first isokinetic dynamometer was introduced in 1967 (Hislop et al., 1967), isokinetic dynamometers became popular equipment for strength evaluation and rehabilitation. There are several different dynamometers (e.g. Kin-Com^{TM}, Cybex^{TM}, Lido^{TM}, and Biodex^{TM}). Some studies (Harding et al., 1988; Li et al., 1996)had been conducted and revealed high reliability of dynamometers in measuring isokinetic concentric and eccentric knee joint strength. Rherson et al. (1998) evaluated the repeatability of the test method of the isometric quadriceps force (IQF). The quadriceps isometric strength was repeatedly tested at 50° and 25° of knee flexion. The time interval between the first test day and second test day was 7 days. The results showed that the IQF method was repeatable. There was no significant difference between the Day 1 test and Day 2 test.

The hip position will influence the knee isokinetic strength values because the RF and BF are biarticular muscles. Worrell et al. (1989) investigated the knee joint strength at seated position and supine position. The results showed the hamstring and quadriceps peak torque values were greater in the seated position than in the supine position. Worrell et al. (1990) further studied the effect of supine and prone body positions on hamstring muscle strength. They revealed that hamstring average torque generated from the prone position was significantly greater than from the supine position.

Isokinetic test speed also has an effect on the peak torque values generated by the knee flexor and extensors. Horstmann et al. (1999) determined that for people at age 55 (SD = 3.8) years, the isokinetic concentric quadriceps peak torque (PT) decreased from 159 (SD = 30) Nm at 60°/s to 83 (SD = 12) Nm at 300°/s. The isokinetic concentric hamstring PT also decreased from 93 (SD = 19) Nm at 60°/s to 74 (SD = 13) Nm at 180°/s, but from 180°/s to 300°/s, the PT of hamstring remained constant. Worrell et al. (1989) measured the quadriceps and hamstring isokinetic concentric strength at 60°/s, 180°/s and 240°/s. They found that as the testing speed increased, the quadriceps and hamstring peak torque value decreased.

Total Knee Arthroplasty

Total knee arthroplasty (TKA) has been used since 1950s. The primary purposes of a TKA are to provide mobility, stability, and freedom from pain to a knee joint exhibiting severe osteoarthritic (OA) or rheumatoid arthritic (RA) degeneration and other changes. Before TKA design became fairly sophisticated, an arthrodesis (A permanent fixation of the joint by surgery) was the recommended treatment of OA and RA. However an arthrodesis could not provide mobility to the knee (Riley, 1983).

The Categories of Total Knee Replacement Designs

Over the last half century, the design of TKA has undergone several basic design changes. Basically, there are three principle categories of TKA design based on: a) the level of constrained vs. and non-constrained designs; b) whether or not the PCL is sacrificed; and c) the number of flexion/extension radii.

Constrained and non-constrained designs.

The typical constrained design is a hinged design. Thus, a constrained design does not require the natural ligaments for knee stability. Walldius introduced the first acrylic hinged design in 1951. The hinged design has some advantages. First, the hinge replaces the cruciate and collateral ligaments and provides stability to the knee joint. Second, the hinge allows flexion/extension in the sagittal plane. Third, the TKA components are easy to implant. Fourth, this TKA design can correct severe knee deformity.

The disadvantages of a hinged design, however, are obvious. According to Vince (1993), first, the hinged design TKA has a high rate of loosening and infection. Second, the hinged TKA can not duplicate complete knee motion. So, the normal knee function could not be fully restored. Third, the hinged TKA implant requires sacrificing a large amount of bone that makes the future revision or fusion difficult. Since the late 1970s, the constrained design was therefore abandoned.

Non-constrained TKA designs include semi-constrained designs and non-constrained designs. A semi-constrained design maintains the stability of the knee joint partially due to the prosthetic design as well as the ligaments retained (Riley, 1983). A total condylar replacement with the PCL sacrificed is an example of a non-constrained TKA.

A non-constrained TKA is designed to retain all of the major knee ligaments, thereby allowing the ligaments to maintain the joint stability, e.g., a total condylar replacement with ACL and PCL retention. However the installation of the non-constrained TKA components is difficult because of the difficulty implanting the TKA with the ligaments intact. The non-constrained TKA has been, for the most part abandoned.

PCL- retention and posterior stabilized TKA.

A PCL-retention TKA design should conserve PCL function so that the PCL can restrict the posterior displacement between the femur and tibia during knee FLEX/EXT. In this type of design, the tibial component surface where contact is made with femoral component is relatively flat. The flat surface allows femoral rollback movement, yet preserves motion and reduces interface stresses (Walker, 1996). The disadvantage of this design is that the PCL is easily maltensioned during surgery (Insall, 1996). A lax PCL can't provide proper restriction to the posterior shear force, but an overtightened PCL limits flexion movement and causes knee pain (Insall, 1996).

The posterior stabilized TKA (PS) design was first introduced in 1978 (Scuderi et al., 1996). The PS design incorporates an inter-condylar tibial spine and a horizontal femoral cam. The spine and cam mechanism is designed to substitute for the functions provided by the PCL. Furthermore, because the tibio-femoral articulation of the PS design is convex in the tibial direction, in both the frontal and the sagittal planes, maximum conformity is thought to be achieved (Scuderi et al., 1996).

Multi-radius and single-radius TKA.

Gunston (1971) introduced the first polycentric TKA design, i.e., created multi-radius of FLEX/EXT throughout knee range of motion (M-RAD), which was also the first non-hinged TKA design. Gunston's (1971) original idea is based on the classical theory that normal knee kinematic characteristics in the sagittal plane exhibit several instantaneous centers of rotation, which are located in the femoral condyle. As Gunston intended to restore normal knee functions in his TKA design, there were multiple radii for this TKA as well. Since then, most of the TKA designs followed this idea (see Table 2.2).

Table 2.2. The locations of the radii (R1 – R3) as a percentage of the anteroposterior length of the femoral component for five different multi-radius TKRs (Hoshino, 1997).

Radius #	Total Condylar (TC)	Insall Bersteins PS	Kinematic Condylar (KC)	Miller-Galante (MG)	Interax (IX)
R1	51.1%	50.5%	52%	72.9%	36.2%
R2	83.2%	119.9%	91.2%	43.8%	54.3%
R3				115.6%	38.6%

Recently, however, as previously described, some investigators (Churchill et al., 1998; Hollister et al., 1993) have suggested that the normal knee joint has only one fixed FLEX/EXT axis that rotates about a longitudinal tibial axis. This finding has led to the design of one single-radius TKA. The Scorpio™ (Howmedica-Osteonics, Inc.) was introduced in 1996. It is the only single radius (S-RAD) TKA currently available. It is surmised that the femoral component of Scorpio™ has a single FLEX/EXT axis similar to the location of the FLEX/EXT axis that Hollister et al. (1993) observed for cadavers.

<u>Muscle Activities of TKA Knee Movements</u>

There is limited literature regarding the influence of a TKA on muscle activation of knee joint and other lower extremity muscles. Kelman et al. (1989) recruited eight older TKA patients (age range from 63 to 79 years) with a unilateral limb PCL-retaining TKA (post-surgery time ranged from 7 to 62 months). For both stair ascent and descent movements, EMG activity was greater on the operated side than the intact limb in all muscle groups tested (vastus medialis (VMO), biceps femoris lateralis (BFL), biceps femoris medialis (BFM), and gastrocnemius (GS)). The subphases of weight acceptance and midstance during the descent movement were associated with greater interlimb EMG differences, as the muscle groups of the operated limb exhibited consistently more activation. Although the limbs showed symmetry for dynamic range of knee motion during gait, Kelman et al. (1989) surmised that the non-TKA limb reduced the range of motion to mimic the TKA limb. They also conjectured that the proprioceptive deficit of the TKA limb might explain the higher EMG activity compared to that of the non-TKA limb.

Steiner et al. (1989) evaluated the gait of 11 TKA patients and compared the preoperative and postoperative kinematics and EMG of the TKA limb. They found the quadriceps activity was constant preoperatively, while postoperatively after six month of surgery 50% of the patients developed a phasic quadriceps EMG pattern. In most patients the medial hamstrings and anterior tibialis muscles also became more phasic. The postoperative values for the gastrocnemius during stance phase remained the same as the preoperative values.

Dorr et al. (1988) studied the gait movements of 11 bilateral TKA patients (post-surgery time = 2 years), who had a posterior cruciate-retaining (PCR) and a posterior cruciate-sacrificing (PS) TKA. They collected kinematic, kinetic and EMG data preoperatively and two years postoperatively for walking and stair climbing for the TKA limbs. They reported that during walking, the PCR TKA limb had a 30% more activated VL than that of the PS TKA limb. The long head of the biceps femoris (BF) of the PS TKA limb was activated longer and with greater EMG than the PCR TKA limb. The total activation times of the PS TKA limb were 16%, 28% and 35% more than those of PCR TKA limb for loading response, mid-stance, and terminal stance phases, respectively. During stair descent, the soleus of PS TKA limb had 40% more activity than that of PCR TKA limb during the loading response subphase. The authors surmised that the soleus of the PS TKA limb might substitute partially for the PCL function of posterior drawer during stair descent. Also, the greater varus moment arm and forward trunk lean observed for the PS TKA limb also were thought to contribute to the higher EMGs of VL and long head BF during level walking and stair movements.

The surgical method may be a factor that also causes the muscle activation patterns to change. Parentis et al. (1999) evaluated two different TKA surgical approaches, the VM muscle splitting approach and the median parapatella approach. They found that there were postoperative EMG changes exhibited by the VM muscles that had undergone the VM muscle splitting approach. Whereas none of the patients who had the median parapatella approach showed any significant changes of EMG. 43% of the patients who underwent the VM splitting approach had signs of abnormal changes of EMG activity in the VM.

The EMG activity of the S-RAD TKA limb during strength test was also reported (Wang et al., 2000). Two male TKA patients (average age = 59 yr., average post-operation = 30 mo.) with a unilateral S-RAD (Scorpio^{TM}, Howmedica-Ostionics, Inc.) TKA limb were tested. EMG for quadriceps (VM, RF, and VL) was recorded during isokinetic strength testing. The EMG results showed that the quadriceps of the non-TKA limb exhibited more normalized co-contraction iEMG than the TKA limb during knee flexion. The authors conjectured that, compared to the N-TKA knee joint, the anteroposterior conformity and the posterior-stabilizing post of the TKA might reflect a need for less co-contraction quadriceps EMG during maximal effort knee flexion.

<u>The Isokinetic Strength of Knee Muscles in a TKA Limb</u>

It is necessary to know how the strengths of knee extensor and flexor recover after the TKA surgery. Wigren et al. (1983) evaluated the knee muscle strength of individuals after their knee replacement surgery for up to three years post-operatively. They found that during the first two years after surgery, the maximum isometric strengths of extensor and flexor were significantly increased for the TKA limb. For the TKA limb, the improvement was greater for the knee flexors than the knee extensors. Furthermore, after three years of surgery, there was no difference between the TKA limb and non-TKA limb for knee flexor or extensor strength (except for knee extensors of the female rheumatoid arthritis group).

In addition, Berman et al. (1991) evaluated the isokinetic strength of the TKA knees. They found that the TKA limb hamstring strength attained the strength levels of the intact limb within the period of seven to 12 months after surgery. However, the quadriceps strength of the TKA limb still had a deficit compared to the intact limb after two years post-surgery. Their study also showed that the TKA limb H/Q ratio did improve toward the normal range after two years post-surgery. Wang et al. (2000) also reported that the TKA quadriceps strength did not recover to the normal level of the non-surgical limb after 2.5 years surgery for two out of two participants.

<u>Kinematic and Kinetic Analysis of TKA Knees</u>

<u>Antero-posterior movement and femoral rollback.</u>

Femoral rollback is defined that in the sagittal plane, the tibio-femoral contact point moves posteriorly when the knee joint flexes. Femoral rollback is believed to increase the quadriceps moment arm. Thereby, the knee extension mechanism is enhanced (Andriacchi et al., 1986). So, restoring femoral rollback is one of the requirements of TKA designs. Different TKA designs exhibits different amount of femoral rollback during knee flexion movement. Mahoney et al.

(1994) measured the femoral rollback movement for three different TKRs (Cruciate Retaining (CR), Cruciate Excision (CE), Posterior Stabilized (PS)) and one healthy knee groups. They found that the CR TKA (Miller-Galante. Zimmer. Inc.) knee had a 36% loss in femoral rollback. The CE TKA (Miller-Galante. Zimmer. Inc.) knee had a 70% loss in femoral rollback. The PS TKA (Insall-Burstein, Zimmer. Inc.) knee exhibited only 12% loss in femoral rollback.

Another report from Stiehl et al. (1997) showed that a posterior retaining TKA (LCS™ Depuy Inc.) revealed 4.6 mm femoral rollback in the first 60° of knee flexion during a deep-knee-bend movement. However when the TKA knee moved from 60° to 90° flexion. The femur of the TKA knee exhibited an anterior translation with an average amount of 4.2 mm relative to the tibia.

However, some TKA knees did not reveal the femoral rollback at all. Stiehl et al. (1995) reported that the femurs of the five posterior cruciate retention TKRs (Porous Coated Anatomic, Howmedica, Inc.; Ortholoc, Wright Medical Technology, Inc.; Genesis, Richards Inc.; Anatomic Modular Knee, Depuy Inc., and Miller-Galante, Zimmer Inc) had an anterior translation (average 15 mm) relative to the tibia during the single leg deep-knee-bend movement. In addition, the TKA knees exhibited a jerky discontinuous motion compared to the smooth motion of healthy knee during the flexion.

Dennis et al. (1998) measured the A/P translations of the TKA knee during a deep-knee-bend movement. Both PCR TKRs (Press-Fit Condylar designs, Johnson and Johnson Inc.) (One PCR TKA had a flat insert, the other PCR TKA had a curved insert) revealed no femoral rollback from 0° to 90° of flexion.

<u>FLEX/EXT range of motion of the TKA knee.</u>

The FLEX/EXT range of motion (ROM) of a TKA knee is affected by (a) the knee disease and preoperative ROM. (b) the surgical technique and the treatment of soft tissue of the knee joint. (c) the TKA design (Hoshino, 1997). Hoshino (1997) studied the influence of the TKA design on the FLEX/EXT ROM. Five different TKA groups were investigated. The information of TKA types, participant age and postoperative time were listed in Table 2.3.

The results showed that the postoperative average flexion angle was 102.9° in the TC group, 109.1° in the PS group, 107.6° in the KC group, 106.5° in the MG group, and 116.3° in the IX group. Hoshino (1997) also explained that the smallest curvature of the femoral component and the smallest distance from the joint surface to the height of the posterior femoral component contributed to the greatest ROM in IX TKA group compared to the other four TKA groups.

In addition, compared to the healthy knee, the TKA knee still exhibited a deficit in the ROM. Stiehl et al. (1995) reported that all the five types of the PCR TKA (Porous Coated Anatomic, Howmedica, Inc.; Ortholoc, Wright Medical Technology, Inc.; Genesis, Richards Inc.; Anatomic Modular Knee, Depuy Inc., and Miller-Galante, Zimmer Inc) revealed smaller ROM (90°) than that of the healthy knee (118°) during the deep-knee-bend movement.

Kinematic Characteristics of the TKA Limb during Daily Activities

Many studies have been conducted to analyze the mechanics of movements of the TKA limbs. The comparisons of kinematic characteristics were made either between the TKA limbs and the non-TKA limbs (el Nahass et al., 1991; Ishii et al., 1998; Kelman et al., 1989), or between the posterior cruciate retention (PCR) TKA limbs and the posterior stabilized (PS) TKA limbs (Dorr et al., 1988; Ishii et al., 1998). Also, the Scorpio™ TKA (S-RAD) knee was studied during daily activities (Magnuson et al., 2000).

The TKA vs. non-TKA limbs

Kelman et al. (1989) studied stair ascent and descent movements of eight elderly patients with a unilateral PS TKA limb after an average of 28 months of surgery. They reported that patients exhibited highly symmetric gait patterns. However the EMG data showed that the muscle activities (VM, Gastrocnemius-Soleus, hamstring) were less on the non-TKA limb than

Table 2.3. Information of patients from five different TKA groups.

TKA	Participant No.	Age at the time of surgery (yr.)	Post operation time (yr.)
Total Condylar (TC)	37	68	6.8
Posterior Stabilizer (PS)	47	69	5
Kinematic Condylar (KC)	97	70	3.5
Miller-Galante (MG)	44	66	2.7
Interax (IX)	46	68	1

the TKA limb. The author concluded that the gait symmetry was maintained by limiting motion in the non-TKA limb, so that the good limb mimicked the TKA limb.

On the contrary, Ishii et al. (1998) reported that the peak flexion angle during level walking were less in both the posterior cruciate stabilized (PS) TKA group (Genesis I, Smith & Nephew Richards, Inc.) and posterior cruciate retaining (PCR) TKA group (Genesis I, Smith & Nephew Richards, Inc.) than that of the control healthy group. The authors provide three possibilities to explain this restricted flexion of the TKA limb during walking. One possibility was that the participants had already got used to have a patterned gait due to having arthritis for many years. The second possibility was the loss of the joint proprioception in the TKA limb. The third possibility was the surgical damage to ligaments and capsules of the TKA limb. In addition, the TKA limbs had less INT_R/EXT_R rotations during swing phase than the healthy limb. The authors thought that the ACL deficit of the TKA limb might affect the INT_R/EXT_R rotation movement of the TKA knee.

Similarly, el Nahass et al. (1991) also reported that the motion of the TKA knee was very similar to the healthy knee. el Nahass et al. (1991) used a 3-D magnetic tracking technique to capture knee motions of a TKA group (Kinematic II) (average age = 61 yr.) and an age matched control healthy group during activities of daily living (sitting, standing, level walking, free leg swing, climbing up stairs, and climbing down stairs). The study results showed that the motion patterns for the TKA patients were similar to those of the healthy person in terms of the INT_R/EXT_R knee rotation and femoral A/P translations relative to the tibia. However, the maximum flexion angles of the TKA limb were less than the healthy limbs during level walking (15° less), climbing upstairs (7° less) and climbing down stairs (6° less).

Dorr et al. (1988) also reported that the TKA patients exhibited less knee flexion angles during stance and swing phases of level walking compared to the normal range obtained from the literature.

The posterior cruciate retention (PCR) TKA vs. the posterior stabilized (PS) TKA

It has long been debated whether sacrificing the PCL or retaining the PCL during the TKA surgery. In order to answer this question, several studies have been conducted to directly compare the functional movements of the PCR TKA and the PS TKA limbs.

Dorr et al. (1988) studied the movements of walking and stair climbing of 11 bilateral TKA patients having a bilateral pair of the PCR TKA (Duopatellar or Robert Brigham. Johnson & Johnson, Inc) and the PS TKA (Total Condylar™) after two years of post-surgery. During level walking, the PS TKA limb exhibited more flexion during loading response compared to the PCR TKA limb. The PS TKA limb had a longer flexion moment throughout loading response into midstance than that of the PCR TKA limb. In addition, the PS TKA limb revealed a greater varus moment than that of the PCR TKA limb. Furthermore, as the flexion and varus moments increased in the PS limb, the EMG activities of quadriceps and biceps femoris increased. The authors drew a conclusion that the PS TKA limb was less efficient compared to the PCR TKA limb because the quadriceps and biceps femoris of the PS TKA limb activated more during the level walking.

In Ishii's et al. (1998) study, the differences of the rotations (FLEX/EXT, INT_R/EXT_R, and VAR/VAL) and translations (A/P, M/L, and PRO/DIS) between the PS TKA (Genesis I, Smith & Nephew Richard, Inc.) knees and the PCR TKA (Genesis I) knees were investigated during the level walking. The post-surgery time was 42.6 months for the PCR TKA patients, and 25.9 months for the PS TKA patients. The results showed that the knee motion during the swing phase of gait was similar for both the TKA groups. However, the PS TKA group exhibited greater VAR/VAL angle and greater PRO/DIS translation than the PCR TKA group. The authors suggested that the PS TKA might not reliably provide enough stabilization in PRO/DIS and VAR/VAL directions.

The functional performance of the Scorpio^{TM} TKA knee

Before 2001, there is only one study conducted to analyze the kinetic and kinematic characteristics of the Scorpio^{TM} TKA limb. Magnuson et al. (2000) compared three types of TKA limbs with respect to the knee joint kinematics and kinetics during six activities of daily living (level walking, stair ascending, stair descending, sitting to a chair, rising from a chair, and squatting). In Magnuson et al.'s (2000) study, there were three TKA (PS Scorpio^{TM}, Howmetica-Osteonics, Inc.; PCR Scorpio^{TM}, Howmetica-Osteonics, Inc.; and PS Zimmer IB2, Zimmer, Inc.) groups and a control healthy group. The study results revealed several points. First, compared to the PS Zimmer IB2 TKA limb, both the PCR Scorpio^{TM} TKA and the PS Scorpio^{TM} TKA limbs exhibited closer magnitude of the max net knee moment to that of the control healthy group during stair ascending, stair descending, sit to stand and squat movements. Second, the PCR Scorpio^{TM} TKA limb exhibited more similar max knee powers during level walking, stand to sit, sit to stand and squat movements to that of the healthy control group than the other two types of TKA limbs. In addition, both of the PS Scorpio^{TM} TKA and the PCR Scorpio^{TM} TKA limbs revealed greater max knee powers during stair ascending and stand to sit movements than the Zimmer TKA limbs. Third, compared to the limbs of the control healthy group, all the TKA limbs exhibited a "stiff" knee (less max flexion angle) during level walking, stair ascending, sit to stand, stand to sit and squat movements. The authors explained that the greater femoral rollback associated with the Scorpio^{TM} TKA limbs might contribute to the greater net knee extension moment during varied activities of daily living compared to the Zimmer^{TM} TKA limb.

However, several limitations existed in this study. First, the sample size (n = 5) of each test groups was small. Therefore, no statistical analysis was conducted. Second, the authors ignored the major design differences between the Scorpio^{TM} TKA and the Zimmer^{TM} TKA. As a matter of fact, the Scorpio^{TM} TKA was a single-radius TKA. The Zimmer^{TM} TKA was a multi-radius TKA. The design of the TKA might affect the functional performance of the TKA limb. Third, this study did not analyze the translations (A/P, M/L, and PRO/DIS) and rotations (VAR/VAL, INT_R/EXT_R, FLEX/EXT) of the TKA knees. Therefore, it will be helpful to explain the cause of greater knee extension moment of Scorpio™ TKA limb compared to Zimmer™ TKA limb if the authors knew the actual amount of femoral rollback.

Sit-to-Stand Movement

Rising from a chair (sit-to-stand) is a basic activity of daily living. More than two million persons after age 64 years had trouble in rising from a chair (Dawson et al., 1987). The sit-to-stand movement requires greater knee extension torque generated by quadriceps muscles than level walking and climbing stairs (Berger et al., 1998). Therefore, compared to gait analysis, the sit-to-stand movement is more suitable for evaluation the functional performance of the knee joint. Furthermore, it is evident that the TKA patients have a deficit of quadriceps strength even after two years of surgery (Berman et al., 1991). But it is not known how the weak quadriceps of the TKA limb affects the performance of the sit-to-stand. Also, the most important, the mechanics of the sit-to-stand and the ability of the TKA patients to perform the sit-to-stand movement. The following context provides a guideline of the kinematic and kinetic of the sit-to-stand movement, the mechanical constraints of a performing sit-to-stand movements, the influence of age on kinematics of the sit-to-stand movement, and the validity of the assumption underlining the biomechanical sit-to-stand studies.

Kinematic and Kinetic of the Sit-to-Stand ovements

Phases of the sit-to-stand movement

Although various researchers have chosen slightly different ways to describe the movements that comprise the sit-to-stand, the description of the phases of the sit-to-stand is based on temporal factors. Riley et al. (1991) considered the sit-to-stand as being comprised of four phases. Phase one (flexion momentum phase) starts from when the body moves from its initial position to the instant when the body leaves the chair (lift-off). The upper body (the trunk, hands, and head) flexes about the hips. The center of mass (COM) moves forward and slightly downward. Phase two (momentum transfer phase) starts from the lift-off to the maximum ankle dorsiflexion. The

COM transitions from primarily forward motion to primarily vertical upward motion. Phase three (extension phase) occurs from the time of maximum ankle dorsiflexion to when the participant is at standing position. Phase four (stabilization phase) is the final postural sway phase.

Roebroech et al. (1994) suggested dividing the sit-to-stand into three phases. The acceleration phase starts from the beginning of the movement to the instant when the horizontal velocity of the COM reaches its maximum. The transition phase is from the instant when the horizontal velocity of the COM reaches its maximum to the instant when the vertical velocity reaches its maximum. The deceleration phase is from the instant of maximum vertical velocity of the COM to the end of the movement.

The phases of the sit-to-stand movement can be simplified into two phases. Alexander et al. (1991) suggested using the instant when the body lifting off from the chair to divide the sit-to-stand into two phases. Similarly, Itokazu et al. (1998) also described the sit-to-stand as two phases. Phase one is from initial position to peak hip flexion. From this instant, phase two begins and last until full extension of the knee and hip joints are achieved.

Segmental momentum

The motion of the whole body during the sit-to-stand is dependent on the motions of individual segments of the body (Pai et al., 1991). Pai et al. (1991) designed a sit-to-stand study with three speed conditions (slow, natural, and fast). They found, in the horizontal A/P direction, the head-arm-trunk segment (HAT) contributed more than 50% of the maximum total body linear momentum. When the sit-to-stand speed was increased from slow to natural. The HAT also increased its contribution to the maximum total body linear horizontal momentum. In the vertical direction, the thigh segment contributed more than 60% to the total body linear maximum momentum. The contribution of the thigh segment increased significantly when the sit-to-stand speed increased from slow to natural or from natural to fast.

However, Riley et al. (1991) did not totally agree with the conclusions of Pai et al. (1991). Riley et al. (1991) suggested that the upper body (pelvis, trunk, arms and head) not only contributed the most horizontal linear total body momentum but also the most vertical linear total body momentum. In addition, the upper body horizontal linear momentum may be transferred to vertical linear momentum during phase two of the sit-to-stand movement (momentum transfer phase). The different results between Pai et al.'s (1991) study and Riley et al.'s (1991) study might be the different methods used to calculate the upper body linear momentum. Similarly, Yu, el al. (2000) investigated the effects of angular motions of ankle, hip and knee joints on the whole body linear motions during the sit-to-stand movement. They found that during the sit-to-stand movement, the ankle and hip angular motions were essential to the contribution of the forward horizontal velocity of the whole body. The knee and hip angular motions were essential to the development of the vertical velocity of the whole body. Therefore, the hip joint angular motion was critical to the success of a sit-to-stand movement. This result supports Riley et al.'s (1991) finding.

Mechanical Constraints to the Sit-to-Stand

The amplitude of the trunk flexion and knee flexion will affect the sit-to-stand movement. Doorenbosch et al. (1994) studied the natural sit-to-stand (Nat_STS) and sit-to-stand with full flexion of the trunk (TF-STS). They found that the TF-STS generated smaller knee joint moment but greater hip and ankle joint moments than the Nat-STS. The biarticular hamstrings EMG showed more activity during the TF-STS than during the Nat-STS. However, biarticular RF showed lower EMG activity during the TF-STS than during the Nat-STS. Doorenbosch et al. concluded that a patient with knee problems might be encouraged to choose the TF-STS method for minimizing the knee joint loading.

Schultz et al. (1992) also suggested that flexing the trunk and flexing the knee to allow the feet under the upper body segments would facilitate the sit-to-stand. Given the same chair height, the initial knee flexion position affects hip joint kinematics and kinetics. Fleckenstein et al. (1988) evaluated the sit-to-stand with two different initial knee flexion positions (75° and 105°; full extension = 0°). The results showed that a sit-to-stand performed with an initial 75° compared to 105° knee flexion angle was associated with a greater peak hip-extension moment and a longer time to complete the sit-to-stand movement.

The chair design also influences the kinematics of the lower limbs. Itokazu et al. (1998) analyzed the time required to complete a sit-to-stand when participants used chairs of two different heights (seat height = 100% and 120% of the lower leg height). The results showed that although the total sit-to-stand time was similar for both chair conditions, participants demonstrated a longer time between the lift off to the position of maximum of hip flexion when rising from the lower compared to the higher height chair. Similarly, Burdett et al. (1985) calculated the lower joint angles and moments when rising from a standard chair (seat height = 43 cm) and a specially designed chair (seat height = 64 cm). The participants exhibited smaller knee and hip flexion angles and joint moments when rising from the higher chair than from the standard chair. In the study of (Wheeler et al., 1985), two chairs whose specifications varied (see Table 2.4) were used.

The results showed that the participants who used the special chair chose to place their feet further forward on the ground, and demonstrated greater anterior trunk lean, knee flexion, and greater VL iEMG during the sit-to-stand than those participants who used the standard chair. Therefore, it was harder for participant to rise from a special chair than from a standard chair.

Table 2.4. Standard chair vs. special designed chair (Wheeler et al., 1985)

	Height (cm)	Posterior slant (cm)	Backrest incline	Clearance under front of chair (cm)
Standard	44.0	1.5	15°	34.5
Special designed	44.4	7.1	20°	29.5

Interlimb Smmetry for Limb Kinetics and Kinematics during the Sit-to-Stand

The assumption of symmetry of limb kinetics and kinematics during the sit-to-stand will simplify the data collection and analysis. Most of the previous sit-to-stand studies (Alexander et al., 1991; Fleckenstein et al., 1988; Yu et al., 2000) assumed that the kinematics and kinetics of the sit-to-stand movement were the same for both limbs. However, the validity of symmetry of interlimb during the sit-to-stand was questioned by Lundin et al. (1995). The authors used two force plates and four video cameras to obtain data to calculate the peak joint moments at the ankle, knee and hip joints that were generated by younger (average age ± SD = 22.9 ± 1.0 yr.) and older (average age ± SD = 74.3 ± 4.1 yr.) participants. The results revealed bilateral asymmetries for peak knee joint moments of the younger group (difference between left and right =0.43 % body weight × body height (BW×BH)). For both the younger (0.2% BW×BH) and older (1.09% BW×BH) groups, the peak hip joint moments exhibited significant interlimb differences. Kinematic and ground reaction force data also revealed the bilateral asymmetry. Lundin et al. (1995), therefore, concluded that assuming bilateral symmetry of lower extremity joint moments during the sit-to-stand is not valid.

Influence of Age on the Sit-to-Stand Movement

It is believed that older people have less muscular strength than younger people (Larsson et al., 1978). The change of muscular strength would influence the kinetics of the sit-to-stand movement, which would, in turn, produce different kinematics or would reflect use of compensatory movement techniques. Wheeler et al. (1985) collected kinematic and EMG data of younger people (age range from 22-28, average height =167.1 cm) and older people (age range from 67 to 81 years; average height =160.9 cm) while participants performed the sit-to-stand. The results showed that the older people placed their feet farther back and demonstrated greater forward trunk lean and greater VL muscle iEMG activity than the younger people during the sit-to-stand. Wheeler et al. (1985) hypothesized that strength differences between the younger and older people contributed to the differences between the age groups. However, in Wheeler et al.'s (1985) study, the chair height was not adjusted according to individual body height. The influence of the chair height to the differences between the younger and older people could not be excluded from the study.

The total rising time and body segment rotations were also studied and compared between the younger people (n=17, mean age =23 yr.) and the older people (n=23, mean age = 72 yr.) (Alexander et al., 1991). The results showed that there were no statistical differences in total rising time between the younger and the older people. However, the older people performed greater thigh extension (rotated them closer to a vertical orientation), leg flexion, and trunk flexion than the younger people.

The Sit-to-Stand Movement of the TKA Patients

Very few studies have been conducted to evaluate the mechanics of the TKA patients' sit-to-stand movement. Itokazu et al. (1998) were interested in the relationship between the total passive knee range of motion and the kinematics of the sit-to-stand movement. They separated 46 TKA patients into two groups according to the range of motion of the patients' TKA knees. The results showed that TKA patients with less knee flexion (<100°) generated greater flexion velocity about the hip joints to swing the trunk forward than those TKA patients with a larger degree of knee flexion (>100°). Itokazu et al. (1998) recommended that a minimum of 100° of postoperative flexion was desired for TKA patients.

Although the TKA limb can mimic the movement of the healthy limb during the sit-to-stand, there are still kinematic and kinetic difference between the TKA limb and the healthy limb (Magnuson et al., 2000). In Magnuson et al.'s (2000) study, six activities of daily living including the sit-to-stand were analyzed. Three TKA groups (PS Scorpio™, PCR Scorpio™, Howmedica-Osteonics, Inc.; PS Zimmer™, Zimmer Inc.) (n = 5) and one healthy group (n = 5) were selected. The healthy limb revealed less minimum knee angle and greater maximum knee angle during the sit-to-stand than those of the TKA groups. The healthy limb also revealed greater maximum knee extension moment than that of the TKA groups. In addition, when comparisons were made among the TKA limbs, the Zimmer™ (M-RAD) TKA limbs had smaller minimum knee flexion angle than the other two Scorpio™ (S-RAD) TKA limbs. However, the Zimmer™ TKA limbs appeared to have less maximum knee extension moments than that of the other two Scorpio™ TKA limbs. In this particular study, Magnuson et al. (2000) did not conduct statistical analysis because of the small sample size. The three dimensional kinematics of the knee were also not available in this study. Further study is warranted to quantify the kinematics of the S-RAD TKA knee during the sit-to-stand.

Stand-to-Sit Movement

After reviewing the literature, only a few studies focusing on the sitting down movement (Kerr et al., 1997; Kralj et al., 1990). Kralj et al. (1990) defined the sitting down movement as the following four phases by using the force plate data. The initiation (phase I) was from quiet standing to stooping posture. The descending (phase II) was from stooping to the instant of seat contact. The seat loading (phase III) completed transferring the weight from the legs to the seats. The stabilization (phase IV) was for adjusting the body balance. Kerr et al. (1997) also defined the stand-to-sit movement as four phases by looking at the segmental movement. The forward lean (forward movement of the trunk), the vertical displacement (downward movement of the trunk), the knee angular displacement (flexion of the knee), and recovery (backward movement of the trunk). Kerr et al. (1997) reported that the initiation of knee angular displacement occurred before the initiation of vertical displacement. However, Kerr et al. (1997) could not find a consistent pattern of forward lean during the stand-to-sit movement.

Summary

In this literature review chapter, relevant studies related to the function and structure of the knee joint are included. Some conflicts exist among the studies. Regarding the knee mechanics, the most controversial issue has been related to the number and location of the axis/axes of knee

FLEX/EXT. The methods of the studies may account for some of the conflicting results. It is interesting to note that co-activation of the knee extensor and flexors will assist the cruciate ligaments to stabilize the knee joint during the FLEX/EXT movement (Baratta et al., 1988). Therefore, the knee muscle co-activation level might reveal the stability condition of the knee joint. The TKA section clarifies the different types of TKA. The Scorpio^{TM} (Howmedica-Osteonics, Inc.) TKA is the first S-RAD TKA. It is still lacking information to the functional performance of the Scorpio^{TM} TKA limb. When comparisons are made between a TKA limb and a healthy limb, there are several major differences. A) the hamstring strength of the TKA limb can obtain the strength level of the healthy limb within the seven to 12 months after surgery. However, the quadriceps strength of the TKA limb still can not recover to the level of the healthy limb (Berman et al., 1991). B) the TKA knee has less passive ROM than the healthy limb (Stiehl et al., 1995). C) the TKA limb also exhibited a stiff knee pattern during level walking, climbing stairs (Dorr et al., 1988; el Nahass et al., 1991). D) the TKA limb exhibited greater muscle activation level than the healthy limb (Kelman et al., 1989).

To the best of our knowledge, only a few studies (Itokazu et al., 1998; Magnunson et al., 2000) are found to date that are focused on the mechanics of the TKA wearers during the sit-to-stand, which is one of the most challenging activities of daily living. Itokazu et al. (1998) observed that the knee ROM affected the sit-to-stand angular kinetics and suggested a minimum of 100° of knee flexion was desired for the TKA patients. Further analyzing the sit-to-stand movement is helpful to understand how particular elements of a TKA design may allow a TKA user to more easily move from a sitting to a standing position.

Although the stand-to-sit movement is an important daily activity, unfortunately, very few studies are available in the literature. Additional studies are needed in order to document the knee joint kinematics and knee muscle activation patterns during stand-to-sit movement. Furthermore, it is beneficial to investigate stand-to-sit movement of TKA patients for improving the TKA designs.

CHAPTER 3

A BIOMECHANICAL COMPARISON BETWEEN THE SINGLE-RADIUS AND MULTI-RADIUS TOTAL KNEE ARTHROPLASTY SYSTEMS FOR THE SIT TO STAND MOVEMENT[1]

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Abstract

Compared to the design of a traditional multi-radius (M-RAD) total knee arthroplasty (TKA), a single-radius (S-RAD) TKA has a longer quadriceps moment arm and a fixed center of rotation in the femoral component. It is not known if the S-RAD TKA could enhance the knee extension mechanism and provide adequate tension to the collateral ligament during daily activities. As the sit-to-stand movement requires greater knee extension moment than walking and stair climbing (Berger et al., 1988), analyzing TKA patient's sit-to-stand movement could help discover the effect on the functional movement due to the difference of the TKA designs. The purpose of this study was to investigate if there were biomechanical differences between the S-RAD and M-RAD TKA groups for the sit-to-stand movement.

Sixteen unilateral, posterior-stabilized TKA participants (8 S-RAD and 8 M-RAD) performed 4 trials of the sit-to-stand test. Three dimensional kinematics and knee flexor and extensor electromyography (EMG) were collected during each trial. One-way ANOVAs were used for statistical analyses ($\alpha = 0.05$).

Compared to the M-RAD group, the S-RAD group demonstrated decreased performance time, trunk flexion displacement and velocity. The S-RAD group also exhibited less knee extensor and co-activation flexor EMG than the M-RAD group. In addition, a briefly distinct valgus motion was exhibited by more M-RAD TKA limbs during trunk flexion phase than S-RAD TKA limbs. However, kinematic comparisons of the non-operated limbs were not significantly different between TKA groups.

The statistically significant differences between-group comparisons of the TKA limbs appear directly related to implant design. Greater reliance on generating vertical momentum via trunk flexion motion and generating more TKA limb knee extensor muscle activity was demonstrated by the M-RAD patients to compensate for a reduced knee extensor mechanism. The brief valgus motion seen in the M-RAD TKA limbs during the initial sit-to-stand phase suggested that the collateral ligaments of the M-RAD TKA limb could not effectively control the medio-lateral knee

stability. Also, the greater hamstring co-contraction activity of the M-RAD TKA limbs helped increase varus/valgus stability during sit-to-stand. In conclusion, the M-RAD group displayed a relatively weak knee extension mechanism by exhibiting compensatory adaptations and significant quadriceps activation. Also, the mid flexion instability was evident in the M-RAD TKA limb as it demonstrated greater hamstring co-contraction. However, enhanced knee extension mechanism and stable TKA knees seen in the S-RAD group revealed the advantage of the S-RAD TKA design.

Keywords: Total knee arthroplasty; Sit-to-stand; Kinematics; Electromyography

Introduction

Although implanting soft tissue (joint capsule) into the knee joints of patients with severe tibio-femoral joint deterioration began as early as 1863 (Vince, 1993; Verneuil, 1863) only since the 1950s the total knee arthroplasty (TKA) has become the standard method to treat late stage osteoarthritis and rheumatoid arthritis (Walldius, 1953; Riley, 1983). As the demand for TKA surgery doubles in the US during the next 30 years (Freund et al., 1997; AAOS, 2000), and the trend of longer life spans continues, the wear time of a TKA implant and the physical function of the TKA limb become more significant.

The ultimate goal of a successful TKA would be to regain the functional ability necessary for the patient to perform desired physical activities and tasks for the longest wear time possible and without inducing secondary medical problems. Therefore, the arthroplasty knee should have similar mechanical characteristics as an intact knee. Thus, to allow typical knee motions and mechanics, an appropriate TKA design should replicate the locations and motions of the axes of rotation of typical knees. However, for typical knee flexion/extension (FLEX/EXT) motion, the true location and orientation of the axis is not uniformly agreed upon (Hollister et al., 1993; Frankel, 1971; Fick, 1911). Furthermore, the locations and orientations of typical knee axes are difficult to ascertain *in situ*. First, due to varying methodologies, a variety of theories exist to explain the instantaneous orientations and locations of the knee flexion/extension (KN-FLEX/EXT) axis (Zatsiorsky, 1998). Second, it has been reported that there is considerable variability among people for location, orientation and movement of the FLEX/EXT axes (Churchill et al. 1998).

To provide optimal KN_FLEX/EXT function and duration of TKA wear, TKA designs have been based primarily on the most common theories regarding the location(s) and orientation(s) of the KN_FLEX/EXT axis (Gunston, 1971; D' Lima, 2001). Until recently, for the majority of TKA designs, the "J-curve ICR" theory has been the basis for the desired KN_FLEX/EXT axis/axes. This notion is based on observations that estimated ICRs form an easily definable "J-shaped" path (when obtained from static, sagittal plane radiographs) that suggest that the FLEX/EXT axis must constantly shift during FLEX/EXT (Frankel, 1971; Fick, 1911). A variation of this idea has been used in TKA design, including the multi-ICR TKA designs of this study (S-7000^{TM}, Howmedica-steonics, Inc. & P.F.C.^{TM}, Johnson & Johnson Inc.). It is common that the M-RAD TKA has two or more ICRs in the femoral component (Hoshino, 1997) (Figure 3.1a).

The single-ICR theory is based on the premise that there is only one location for the FLEX/EXT axis, but the FLEX/EXT axis is fixed to the femur (Hollister et al., 1993; Churchill et al., 1998; Pinskerova, 2000). Hence, if the femur internally (INTN) or externally (EXTN) rotates, the FLEX/EXT axis also rotates, and no longer aligned perpendicular to an externally-fixed sagittal plane. Although this single ICR theory was proposed first in 1993 (Hollister, 1993), based on our current knowledge, until recently, the Scorpio^{TM} Total Knee Arthroplasty System (Howmedica-Osteonics, Inc.) was the only TKA design incorporated the single-ICR theory (Figure 3.1b). In addition, although arthroplasty surgeons seek evidence to determine if the use of a single-ICR design is more beneficial to a patient than a multi-ICR design (Mahoney, 2002), little is known about the effects of the mechanical characteristics of a single-ICR design on functional benefits to the user.

The major biomechanical difference that could lead to functional performance differences for the patient between a traditional TKA with multiple FLEX/EXT axes and their associated radii of rotation (M-RAD) to a single FLEX/EXT axis TKA and its radius of rotation (S-RAD) is the locations of the KN_FLEX/EXT axes. Consequently, as those FLEX/EXT ICRs of the M-RAD TKAs used in this study are more anterior than the S-RAD TKA ICR (D' Lima, 2001), it is likely that the M-RAD compared to the S-RAD TKA quadriceps moment arm is shorter, hence reducing the effective knee extensor mechanism.

Furthermore, differences for KN_FLEX/EXT axis locations between the designs are related to the radius of rotation lengths, as only the M-RAD TKA abruptly shifts from a longer to a shorter radius during KN_FLEX that may cause transitory slack of the relevant fibers of the collateral ligaments, thereby creating temporary medio-lateral knee instability. For the M-RAD TKAs used in this study, the shift from the first FLEX/EXT axis to the second FLEX/EXT axis usually occurs between 30° and 45° of knee flexion (0^o = full extension) (www.osteonics.com). This angle appears to correspond approximately to the knee angles when mid-flexion instability occurs for only M-RAD patients during knee extension movements that require raising the body (Mahoney, 1999). As the M-RAD TKA knee flexes, the FLEX/EXT axis will shift from P1, which has a longer radius of rotation (R1) to P2, which has a shorter radius of rotation (R2) (Figure 3.1a). Theoretically, this transition from R1 to R2 reduces the distance from the femoral attachments of the collateral ligaments to the tibio-femoral contact point. Consequently, collateral ligament tension also may decrease, thereby creating the mid-flexion instability at the knee joint that is often reported by M-RAD patients (Mahoney, 1999). Because the fixed FLEX/EXT axis of the S-RAD TKA results in a fixed radius of rotation (R1 in Figure 3.1b) throughout the range of knee motion, it is reasonable to expect that the collateral ligaments of the S-RAD TKA should better maintain adequate tension throughout the entire range of motion than those of the M-RAD TKA.

Unfortunately, experimental evidence is lacking to demonstrate the knee strength and kinematic difference between the M-RAD and S-RAD TKA limbs during common daily activities. Although sit-to-stand is a necessary movement in Western culture, it is even more demanding than walking and stair climbing, requiring greater KN_FLEX/EXT muscle moments (Berger et al., 1988). It is potentially limiting sit-to-stand ability for someone whose knee muscle strength is compromised, e.g., recent post-operation TKA patients. Based on the few existing studies whereby the biomechanical characteristics of the sit-to-stand as performed by TKA and non-TKA participants were compared, it appears that TKA patients exhibit compensatory adaptations to improve stability, counteract reduced KN_FLEX ROM and reduce the knee muscle and reaction force demands (Su et al., 1998). It is not known if the mechanical differences related to the KN_FLEX/EXT axes between the M-RAD design and the S-RAD design could cause functional differences between users. As this study is part of a larger study, the primary purpose of this study was to investigate for the sit-to-stand movement, whether the use of an S-RAD TKA design compared to the use of an M-RAD TKA design by unilateral participants would require less KN_EXT muscle activation and less abduction/adduction (ABD/ADD) and KN_FLEX muscle co-activation. The secondary purpose of this study was to investigate if the M-RAD participants demonstrate more kinematic evidences of adaptations to compensate for the TKA limb than the S-RAD participants.

Hypotheses are provided here for the advisory committee- will be removed for manuscript due to manuscript length limitation. The S-RAD TKA limb compared to the M-RAD TKA limb was hypothesized to exhibit less: a) sit-to-stand time; b) maximum trunk flexion angle prior to rising; c) trunk flexion angular velocity; d) normalized quadriceps RMS EMG; e) normalized hamstrings RMS EMG; f) ABD/ADD angular displacement.

Methods

Participants

Sixteen individuals participated in this study. Eight of the individuals had a unilateral S-RAD TKA (Scorpio™ PS, Howmedica-Osteonics, Inc.). The remaining eight individuals had a unilateral M-RAD TKA (S-7000™ PS, Howmedica-Osteonics, Inc.; P.F.C. ™ PS Johnson & Johnson, Inc.). Participants' other characteristic information are presented in Table 3.1. All the TKA surgeries were performed by the same surgeon. Participants were prescreened based on the following criteria:

- Had no history of stroke, heart or diabetes, or other major diagnosed health problems.
- Had the TKA surgery at least 18 months prior to the study.
- Had medical clearance from his or her physician to participate in the study.

- Had not been taking any drugs that had the potential to adversely affect performance.
- Was free from hip, knee, ankle and low back pain.
- Had a score greater than 90 on the Knee and Function subsections of the Knee Society Clinical Rating System (Appendix A) (Insall, et al. 1989).
- Had passive knee flexion ROM values greater than 100°.

Instrumentation and Experimental Setup

Instrumentation

A Peak Motion Measurement System™ (Peak Performance Technologies, Inc) was used to collect the kinematic data, that include: three genlocked high-speed video cameras (Pulnix™, Model TM640) with a sampling rate of 120 Hz and a shutter speed of 1/1000 s; three S-VHS VCRs (JVC™, Model BR-5378U); Peak Performance™ 21-point calibration frame ($2.2185 \times 1.583 \times 1.5035$ m^3); Peak Performance™ event video control unit (EVCU) and 16 channel A/D interface; and Peak Motus™ V. 4.3.1 software package. Two sets of different sizes reflective markers (diameter = 2.0 cm and 1.2 cm, respectively) were used.

A 16-channel MYOPAC™ EMG system (Run Technologies, Inc.) was used to collect the differential input surface electromyographic (EMG) signals of the vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF) and semitendinosus (ST) during sit-to-stand tests. Disposable electrodes (Blue Sensor™, Medicotest, Inc.) were used to collect the EMG signals. The average inter-electrode distance was 2.3 cm. A reference ground electrode was attached over the distal radius of the wrist. The EMG signal (sampling rate =1080 Hz) from the electrodes was sent to a waist pack and amplified (gain = 1000 to 10,000), then transmitted to a receiver and amplifier (MPRD-101 Receiver/Decoder unit) (CMRR = 110 dB) via an optical fiber cable. The analog EMG signal from the receiver was digitally transformed via a 12-bit A/D board.

A KIN-COM III^{TM} isokinetic dynamometer (500 Hz) (Chattecx Corp, USA) was used for conducting isometric strength testing for knee extensor and flexor muscles in order to obtain the EMG of the VM, VL, RF, BF, and ST during maximal voluntary contraction (MVC).

Three wood blocks with different heights (10 cm, 20 cm and 30 cm) were used for the participants to sit upon during the sit-to-stand tests.

Experimental Setup

The placements of the three cameras are illustrated in Figure 3.2. Video signals from cameras and EMG were synchronized through the EVCU.

The participant's body was tested from one side to the other. The EMG electrodes and reflective markers were placed only on the tested side. After placing the EMG electrodes on the participant, reflective markers were placed on the tested side of the body. Two configurations of reflective markers, dynamic (DYN) and anatomical (ANA) were used (Table 3.2). Some markers served as both DYN and ANA markers. The purpose of the ANA markers during kinematic data reduction were to establish the unit vectors for the segmental coordinate systems of shank and thigh, while the DYN markers were used during data reduction to reconstruct the location of ANA markers. Thus, for each segment, DYN and ANA markers locations were captured when the participant was standing quietly before data collection of the actual sit-to-stand trials, while only the locations of DYN markers were captured during data collection.

Protocol

- A consent form (Appendix B) was signed by the participant.
- A pretest questionnaire was administered (Appendix C).
- The participant's body mass, body height, and lower leg length were measured.
- Five minutes low intensity bicycling on a stationary cycling ergometer was performed as a warm-up.

- Passive hip and knee joint stretching were performed with the assistance of a certified athletic trainer.
- The maximum knee extension and flexion angles were measured by the athletic trainer.
- The sit-to-stand tests were administered.
- The strength test was administered.
- The posttest questionnaire (Appendix D) was conducted to obtain participant's perceptions of the quality of his/her physical functioning in order to qualitatively assess his/her satisfaction with the TKA.

<u>The general protocol for the sit-to-stand tests</u>

- The height of the blocks was adjusted so that the participant could sit on the block comfortably with both thighs parallel to the floor at approximately 90° of knee flexion.
- The right side of the body was tested first. In order to capture the locations of all the ANA and DYN markers on the shank and thigh to establish the relationship between ANA and DYN markers, the participant was videotaped for 10 sec. while standing quietly.
- In order to obtain the reference angular displacements in the three directions (FLEX/EXT, ABD/ADD, and INT_R/EXT_R) between the femur and the tibia for further calculating the change of angular displacement of the knee joint, the participant was videotaped for 10 sec. while he/she was standing naturally.
- In order to obtain a baseline value for future EMG data processing, the participant sat quietly and relaxed on blocks while three sec. of EMG data were collected.
- For the actual sit-to-stand task, the participant sat on the blocks with arms across the chest, and the feet were placed shoulder width apart on the floor. To perform one trial, after the tester gave a verbal signal, the participant stood up as rapidly as possible and maintained the standing position for five sec. To ensure collecting a good trial (the participant stood up by

himself/herself without losing balance), a total of four trials were administered before repeating the protocol for the other limb.

- After testing one leg, the participant took a 5-min. rest. During this period of time, reflective markers and the EMG electrodes were placed on the other leg. Then the participant was instructed to turn around 180° for data collection of the other leg.
- After finished sit-to-stand tests, isometric strength tests were conducted. The N-TKA limb was tested first. Prior to strength tests, baseline EMG signals were collected for three sec. while the participant maintained a relaxed position for the test limb.
- Isometric strength tests were administered at 60° for knee extensor and 30° for knee flexor. EMG data of the VM, VL, RF, BF and ST were collected during isometric strength tests. The isometric EMG data were used for normalizing the EMG signals during the sit-to-stand tests.

Data Reduction

EMG data reduction

EMG data were divided by the gain factors that were used to magnify the EMG signal during data collection and adjusted to the baseline value. Rectified EMG values were expressed as a percentage of the mean rectified EMG obtained during the maximal effort isometric tests. Using the normalized rectified EMG, root mean squared (RMS) data were generated as follows:

$RMS = \{1/T\int_0^T (rEMG(t))^2 dt\}^{1/2}$,

where rEMG(t) represented the rectified EMG at time t, dt was the sampling rate (1/1080 s.), and T was the moving window size of 0.026 s. (28/1080 s.). The mean of the normalized RMS_i was calculated for each of the four angular intervals (15°-30°, 31°-45°, 46°-60°, and 61°-75°) (RMS_i, where i represented the specific angle interval).

Kinematic data reduction

Peak Motus™ 4.3.1 software was used to track the marker locations for each camera and to reconstruct the three dimensional coordinates of these markers by using the Direct Linear

Transformation (DLT) method (Peak Motus^{TM} manual, 1998). The raw data were then smoothed using a Quintic Spline method (Jackson, 1979).

There was a three-part process to derive the knee joint angles demonstrated during the actual sit-to-stand trials (see Appendix E for detail). First, the data collected when the participant stood with the ANA and DYN markers presented (see Table 3.2 for their locations) were used to construct an anatomical segment coordinate system (ASCS) and a dynamical segment coordinate system (DSCS) for each segment (thigh and shank). The relationship between the ASCS and DSCS was represented by a transformation matrix. Therefore, during the actual sit-to-stand trials, the location of the ASCS of each segment could be obtained through the current DSCS location and the transformation matrix.

Second, a knee joint coordinate system (JCS) to describe the relative motions between the thigh and shank segments was established based on the ASCS of both segments (Grood & Suntay, 1983). As shown in Figure 3.3, the unit vectors $\mathbf{e_1}$, $\mathbf{e_2}$, and $\mathbf{e_3}$ established the JCS of the knee. $\mathbf{e_1}$ and $\mathbf{e_3}$ were the unit vectors along the mediolateral axis of the thigh (X_{TH}) and the longitudinal axis of the shank (Z_{SH}), respectively, where the X_{TH} was the X-axis of ASCS of the thigh and Z_{SH} was the Z-axis of ASCS of the shank. Therefore, $\mathbf{e_2}$ was the unit vector of the floating axis F_2:

$$\boldsymbol{e_2 = (e_3 \times e_1)/| e_3 \times e_1|}$$

Third, the knee angles for each of the three angular directions (FLEX/EXT, ABD/ADD, and INT_R/EXT_R) during the sit-to-stand actual trials were expressed relative to the corresponding natural standing knee angles (Grood & Suntay, 1983). Table 3.3 shows the calculations of these angles.

In addition, min and max of INT_R/EXT_R and ABD/ADD angles were calculated. Percentage time reaching the min and max of INT_R/EXT_R and ABD/ADD angles were generated. The displacements of INT_R/EXT_R and ABD/ADD during the sit-to-stand were also generated.

In addition, the hip flexion angle was defined as the angle between the connection line of iliac spine and great trochanter and the longitudinal axis of the thigh (Z_{TH}). The trunk forward lean angle was defined as the angle between the connection line of iliac spine and acromion and the antero-posterial horizontal line. The thigh and shank inclination angles were defined as the angles between the antero-posterial horizontal line and the longitudinal axes of thigh (Z_{TH}) and shank (Z_{SH}), respectively.

The total sit-to-stand time was calculated from the beginning of the trunk movement to the end of the trunk movement. Furthermore, the maximum trunk flexion, average angular velocity of the trunk flexion, maximum hip flexion, max shank flexion, and percentage time reaching the above critical events were generated.

<u>Statistical Analysis</u>

The relative knee INT_R, EXT_R, ABD, and ADD displacements, maximum and minimum shank, thigh, trunk, and hip angles during the sit-to-stand tests were selected as dependent kinematic variables. The percentage times of the above critical events relative to the sit-to-stand movement time (% TOT-T) were also selected. The normalized RMS EMG of the VM, VL, RF, BF, and ST for the four equal angle intervals (15°-30°, 31°-45°, 46°-60°, 61°-75°) during sit-to-stand tests were selected as dependent EMG variables.

Statistical analyses were performed using SPSS^{TM} (V.10, Chicago, IL). As shown in Table 3.1, the age and post-operation time were statistical significant between the two TKA groups. Thus, one-way ANCOVAs were used to test if the age and post-operation time could have significant effects on the kinematic and EMG variables that we generated in this study. The age and post-operation time were selected as the covariates in the ANCOVA model, respectively. We found that for 47 kinematic and EMG dependent variables, there were one interaction and two significant effects related to the age. In addition, for the same amount of dependent variables, there were two interaction and two significant effects related to the post-operation time. The small number of significant effects from the ANCOVA tests might due to the type I error.

Therefore, the age and post-operation time had a very limit effect on the dependent variables in this study.

Base on the previous ANCOVA results, one-way ANOVAs were used to determine the differences between the S-RAD and M-RAD TKA groups for the kinematic and EMG variables. In addition, as the ABD/ADD starting angle was highly correlated with the ABD and ADD displacement, the ABD/ADD starting angle was selected as a covariate, and a one-way ANCOVA was conducted to determine the differences between the two TKA groups for the ABD and ADD displacements. The significance level was 0.05 for all statistical tests.

Results

Table 3.1 shows participants' characteristics. The S-RAD group (65 ± 5 yr.) was younger and received surgeries (29 ± 11 mo.) later than the M-RAD group (72 ± 7 yr. and 79 ± 25 mo., respectively). However, there were no statistical differences for body height, body mass, knee society scores, and TKA knee range of motion between the two groups.

Appendix F shows the samples of kinematic graphs of the sit-to-stand. The sit-to-stand movement was divided into two overlapping phases. Phase I was the trunk flexion phase that was from the initial movement of the trunk to the maximum trunk flexion (trunk upright position = 0º). Phase II was the vertical displacement phase that was from initial knee extension to full body upright position. The results of sit-to-stand test were reported in the following three aspects: a) the Flex/Ext kinematics of the body, b) the knee joint kinematics, and c) the EMG of the quadriceps and hamstrings.

The Figure 3.4 shows that the average time for the S-RAD group to accomplish the sit-to-stand movement was 1.59 s, which was 0.19 s less than the M-RAD group (p = 0.033). The Figure 3.5 shows that during the phase I, the maximum trunk flexion angle of the S-RAD group was 10º less than that of the M-RAD group (p = 0.014). In Figure 3.6, the S-RAD TKA group tended to have 7º •s^{-1} less trunk flexion velocity than that of the M-RAD group (p = 0.058).

However, both TKA groups had similar trunk recovery velocity during the phase II ($42^{o} \cdot s^{-1}$ for both groups, $p = 0.957$).

The Figure 3.7 shows that the S-RAD TKA limb tended to have less ADD displacement (p = 0.071) than that of the M-RAD TKA limb. However, there was no significant difference of the ABD displacement between the S-RAD and the M-RAD TKA limbs ($p = 0.73$). Furthermore, we failed to find significant differences for ABD and ADD displacements between the S-RAD and M-RAD N-TKA limbs (p = 0.128 and 0.457, respectively).

After reviewing individual's data, we found that seven out of eight M-RAD TKA limbs demonstrated an ABD peak during initial trunk flexion. However, only three out of eight S-RAD limbs showed an initial ABD peak. The Fisher exact probability test was used to determine the difference of this initial ABD peak phenomenon between the S-RAD and M-RAD limbs. A probability value of 0.059 was presented. However, this tendency was not seen between the S-RAD and M-RAD N-TKA limbs. Only two S-RAD and three M-RAD participants showed this initial ABD motion pattern in their N-TKA limbs.

The Figures 3.8 – 3.10 showed the quadriceps EMG results for the TKA and N-TKA limbs. The VM of the S-RAD TKA limb demonstrated significant less RMS EMG than that of the M-RAD TKA limb from 60º to 15º of knee flexion ($p < 0.05$). The VL of the S-RAD TKA limb also demonstrated significant less RMS EMG than that of the M-RAD TKA limb from 60º to 45º of knee flexion ($p < 0.05$). Similar to the VM and VL, the RF of the S-RAD TKA limb showed less RMS EMG than that of the M-RAD TKA limb from 60º to 30º of knee flexion ($p < 0.05$). Furthermore, the VM and VL of the S-RAD N-TKA limb demonstrated less RMS EMG than those of the M-RAD N-TKA limb from 75º to 60º of knee flexion, which was close to the initial vertical displacement phase.

The Figures 3.11-3.12 show the hamstrings EMG for the TKA and N-TKA limbs. As indicated in Figure 3.11, the BF of the S-RAD TKA limb demonstrated less RMS EMG than that of the M-RAD TKA limb from 75º to 15º of knee flexion ($p < 0.05$). In addition, there was a nonsignificant tendency that the ST of the S-RAD TKA limb was less than that of the M-RAD TKA limb from 75º to 45º of knee flexion ($p < 0.07$). Similarly, the ST of the S-RAD N-TKA limb had less RMS EMG than that of the M-RAD N-TKA limb from 75º to 60º of knee flexion ($p < 0.05$).

Discussion

This discussion section is based on the question, "Do the two major design differences between the two TKA types, i.e., a) differences for quadriceps moment arm lengths and b) the existence of one versus two or three radii of rotation lengths, produce functional differences between the two TKA groups during performance of the sit-to-stand. The functional effects of quadriceps moment arm lengths are discussed first.

Functional Differences Due to the Differences of Moment Arm Length between TKA Types

As the moment arm length for the quadriceps force acting on the tibia via the patellar ligament is longer for the S-RAD compared to the M-RAD TKA designs, all else being equal, participants with an S-RAD TKA should be able to generate the necessary knee extensor muscle moment with relatively less knee extension force than M-RAD TKA participants. From another viewpoint, if the M-RAD group could not generate more quadriceps force than the other group, then this group would display compensatory adaptations to help the performer extend the body upwards. In addition, as the M-RAD group was expected to increase the generation of the quadriceps force, the quadriceps EMG would reach a high level. Thus, in the section, we will focus on compensatory adaptations and quadriceps EMG activity.

Compensatory adaptations

In this study, the M-RAD TKA group demonstrated significantly greater sit-to-stand time, greater trunk flexion angle, and a tendency of greater trunk flexion velocity. These findings suggest the existence of the compensatory adaptations in the M-RAD TKA group.

Although our mean values for sit-to-stand time of both TKA groups were less than the sit-to-stand time of normal old adults (1.83 s, SD = 0.71) reported by Alexander (Alexander et al., 1991), as we anticipated, the S-RAD TKA participants used significantly less time to stand up from a seated position than the M-RAD TKA patients. It cannot be conclusively determined from these data why this occurred. However, it is possible that knee extensor strength (i.e., the amount of knee extension muscle moment that can be produced) may have influenced the sit-to-stand time, as a recent study showed that the S-RAD TKA limb could generate greater isokinetic knee extension torque than the M-RAD TKA limb (Mahoney, 2002).

It has been suggested that, during the initial trunk flexion phase, TKA individuals increase trunk flexion to compensate for TKA limb-related weakness (Su et al., 1998). The degree of trunk flexion exhibited during trunk flexion phase was construed by Su (Su et al., 1998) to reflect a means for reducing the amount of knee extension muscle moment required during knee extension phase. In Su's (Su et al., 1998) sit-to-stand study comparing the kinematics of TKA patients with normal subjects, TKA patients displayed greater trunk flexion than normal subjects during the sit-to-stand. (Su et al. (1998) did not document the TKA type used in their study. However, according to the time when they submitted the article (1996 -1997), we surmise that the TKA patients participating in their study were M-RAD TKA patients because only the S-RAD TKA design was on the market in 1996.) Su explained that the TKA patients increased their trunk forward lean as an adaptation that served to reduce the magnitude of the knee extension muscle moment acting on the thigh via reduction of the hip joint reaction-force moment acting in a counter direction. Therefore, for this study, the significantly greater trunk forward lean displayed by the M-RAD compared to the S-RAD TKA participants potentially indicates that the M-RAD TKA group used trunk positioning as part of a TKA limb-related compensatory mechanism as predicted.

The third compensatory adaptation that we found is the M-RAD TKA group tended to increase the trunk flexion velocity during the trunk flexion phase. Although it was not statistically significant (p = 0.058), the M-RAD TKA group showed to have 7 $^{o}\bullet s^{-1}$ more trunk forward lean velocity than that of the S-RAD TKA group. The possible explanation is, when approached to the end of the trunk flexion phase, the trunk flexion is decelerated. During the deceleration stage, the hip extensor muscle groups pull the trunk backward in order to reduce the trunk forward momentum. At the mean time, the hip extensor muscle group creates a counter-torque acting on the thigh and rotate the thigh to a vertical straight position. Through this process, the horizontal momentum of the trunk could be transferred into vertical momentum of the thigh. Therefore, by increasing average trunk flexion velocity, the M-RAD TKA patients could increase horizontal momentum of the trunk, and at the end of the trunk flexion, the horizontal momentum could be transferred into vertical momentum of the thigh. Consequently, the vertical momentum would facilitate standing up. This movement strategy demonstrated by the M-RAD TKA patients suggested that the M-RAD TKA patients tried to use trunk movement to compensate the possible weakness of their TKA limbs.

<u>EMG activity of quadriceps</u>

As predicted, The EMG of the VM, VL, and RF of the M-RAD TKA limb were significantly greater than those of the S-RAD TKA limb during phase II (knee extension phase) of the sit-to-stand. More muscle activation demonstrated in the M-RAD TKA limb reflected greater demand on muscle efforts. As the M-RAD TKA limb has a shorter quadriceps moment arm than the S-RAD TKA limb, in order to accomplish rising from a chair as fast as possible, greater knee extension torque is needed. Thus, greater quadriceps contribution is required for compensating the shorter quadriceps moment arm for the M-RAD TKA limbs compared to the S-RAD TKA limbs. In addition, the N-TKA limb of the M-RAD group exhibited greater VM and VL EMG at the initiation of the knee extension phase (phase II) than the N-TKA limb of the S-RAD group. The possible explanation for this finding is, the M-RAD TKA participants might try to compensate the weakness of their TKA limbs by increasing the effort of the quadriceps of the N-TKA limb.

Mid Flexion Instability

As we mentioned earlier in the introduction, the multiple radii design of an M-RAD TKA could lead to knee mid flexion instability. In this section, we will discuss the ABD/ADD displacement and hamstring co-contraction EMG that would reflect the stability of the TKA knee.

ABD/ADD displacement

Although it was not statistically significant ($p = 0.071$), the M-RAD TKA limb tended to have 4º more ADD displacement than the S-RAD TKA limb. According to the M-RAD TKA design, shorter radii were used from full knee flexion to near 30º of knee flexion. The tension of the collateral ligaments was reduced when the knee traveled within the mid flexion range. Therefore, the collateral ligaments lost the ability to effectively constrain the knee joint in the medio-lateral direction. Thus, during the sit-to-stand movement, as the knee joint moved from flexion to extension, the M-RAD TKA limb tended to have unnecessary more knee ADD displacement than the S-RAD TKA limbs.

In addition, an obvious ABD peak was noticed in the M-RAD TKA limb but not in the S-RAD TKA limb during the trunk flexion phase of the sit-to-stand. When the trunk leaned forward, the upper body weight was transferred from the chair to the knee joints. As the joint load increased rapidly, a stabilization mechanism was required in order to maintain the knee joint stability. With relatively slack collateral ligaments in the flexion position, it was not surprising to see that the M-RAD TKA knee exhibited a distinctive ABD peak during the trunk flexion.

Hamstring co-contraction EMG

It has been suggested that the hamstring co-contraction could stabilize the knee joint (Solomonow et al., 1987; Kasman et al., 1998; Zhang et al., 2001). However, as a biarticular muscle group, hamstrings have multiple functions. First, hamstrings could extend the hip joint and flex the knee joint. In this study, there was no statistical difference ($p = 0.957$) for the trunk recovery velocity during the sit-to-stand movement between the M-RAD and S-RAD groups. This suggested that the contribution level to the hip extension from the hamstrings might be the same for both types of TKA limbs. Second, the hamstring muscle could provide resistance to the tibia anterior shear (Kasman et al., 1998). In this study, both the S-RAD and M-RAD TKAs had similar designs in the geometry of the tibial component. The conformity design between the tibial and femoral components would replace the function of the cut ACL. In a previous studie, we found that the M-RAD TKA limb actually demonstrated less hamstring co-contraction EMG than the N-TKA limbs during the sit-to-stand (Wang et al., 2001). Therefore, we expected that the TKA limbs did not need to increase the hamstring co-contraction level to counteract the tibial anterior shear force. Third, hamstrings could also provide restrain to the ABD/ADD knee motion (Zhang, 2001). As we expected, the M-RAD TKA limb demonstrated greater hamstring co-contraction EMG than the S-RAD TKA limb during the vertical displacement phase. Therefore, the increasing hamstring co-activation level seen in the M-RAD TKA limb might contribute to compensate the loosen tension of the collateral ligament for stabilizing the knee joint in the medio-lateral direction.

In summary, the M-RAD TKA group used compensatory adaptation movement strategies to compensate for the strength deficit of their M-RAD TKA limbs. The M-RAD TKA limb also increased the quadriceps muscle activation level to produce more knee extension torque to compensate for the short quadriceps moment arm. Further, the M-RAD TKA limb might have an unstable knee joint in the medio-lateral direction during the sit-to-stand by showing a tendency of more ADD displacement and greater hamstring co-activation EMG than the S-RAD TKA limbs.

In conclusion, the M-RAD TKA design was not able to help the knee joint to produce adequate knee extension moment with less quadriceps muscle effort. The M-RAD TKA could cause knee joints to have mid-flexion instability during the sit-to-stand. However, the S-RAD TKA could facilitate the knee joint to generate adequate extension moment with less quadriceps effort and maintain a stable knee joint during the sit-to-stand movement.

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Table 3.1. Means ± Standard Deviations for Participant Characteristics.

Variables	TKA group: S-RAD (n = 8)	TKA group: M-RAD (n = 8)
Gender		
Number of male	4	6
Number of female	4	2
TKA type	Scorpio™ PS	S-7000™ PS (n = 4) P.F.C™ PS (n = 4)
Age (yr.)	65 ± 5 *	72 ± 7
Post operation time (mo.)	29 ± 11 *	79 ± 25
Body height (m)	1.71 ± .10	1.72 ± .07
Body mass (kg)	94 ± 14	89 ± 15
Clinical knee society score	95 ± 2	96 ± 2
Functional knee society score	95 ± 8	90 ± 11
TKA Knee range of motion (deg)	110 ± 7	113 ± 8

Note. * indicates significant comparison between the TKA groups (critical $F^*_{1, 14} = 4.60$; $p < 0.05$)

Table 3.2. The DYN and ANA markers' placements

Marker's Title	Description of location	Type of markers
Shoulder	Acromion	DYN
Waist	Lateral iliac spine	DYN
Great trochanter	The center of the great trochanter	ANA & DYN
Mid thigh	Anterior mid thigh	DYN
Lateral epicondyle	Center of lateral femoral epicondyle	ANA & DYN
Medial epicondyle	Center of medial femoral epicondyle	ANA
Proximal anterior shank	2 cm above the center of the tibial tuberosity	ANA & DYN
Distal anterior shank	Anterior side of the shank and 5 cm above the center of the lateral malleolus	ANA & DYN
Rear distal shank	Rear side of the shank and 5 cm above the center of lateral malleolus	ANA & DYN
Lateral malleolus	Center of the lateral malleolus	DYN
Heel	2 cm below and 2 cm posterior the center of lateral malleolus (on calcaneus)	DYN
The 5th metatarsal head	Lateral edge of head of fifth metatarsal	DYN

Table 3.3. Calculation of the knee flexion/extension (FLEX/EXT), abduction/adduction (ABD/ADD), and internal/external (INT_R/EXT_R) rotation angles (Grood & Suntay, 1983)

Angle	Right knee	Left knee
FLEX(-)/EXT(+) angle	$arccos\ (\boldsymbol{e_2} \bullet \boldsymbol{k_{TH}}) - \pi/2$	$arccos\ (\boldsymbol{e_2} \bullet \boldsymbol{k_{TH}}) - \pi/2$
ABD(+)/ADD(-)	$arccos\ (\boldsymbol{e_1} \bullet \boldsymbol{e_3}) - \pi/2$	$\pi/2 - arccos\ (\boldsymbol{e_1} \bullet \boldsymbol{e_3})$
INT_R(-)/EXT_R(+)	$\pi/2 - arccos\ (\boldsymbol{i_{SH}} \bullet \boldsymbol{e_2})$	$arccos\ (\boldsymbol{i_{SH}} \bullet \boldsymbol{e_2}) - \pi/2$

Note. See Figure 3.3 for explanation of unit vectors.

a) b)

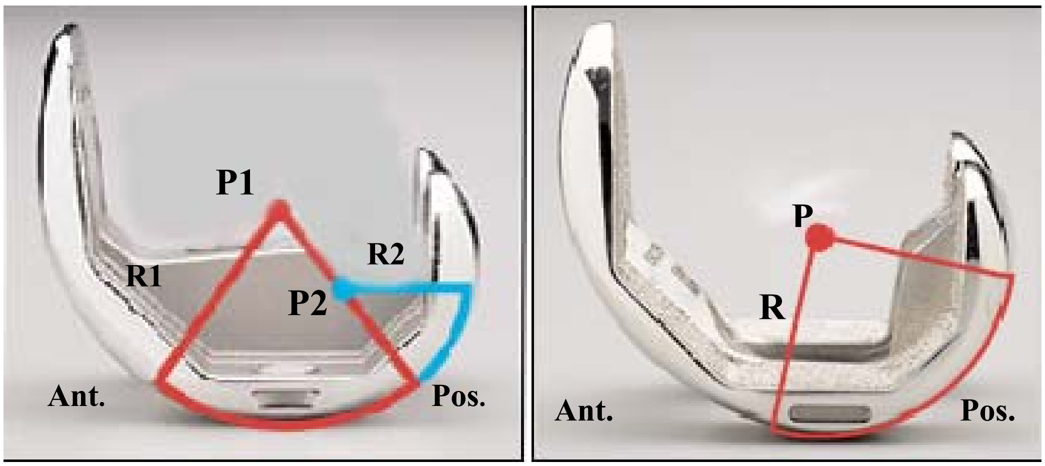


Figure 3.1. Lateral views of left knee femoral components of the a) M-RAD TKA and b) S-RAD TKA. P1, P2, and P represent the centers of flexion/extension rotation, and R1, R2, and R represent the corresponding radii of rotation. (Courtesy of Stryker-Howmedica-Osteonics Inc.)

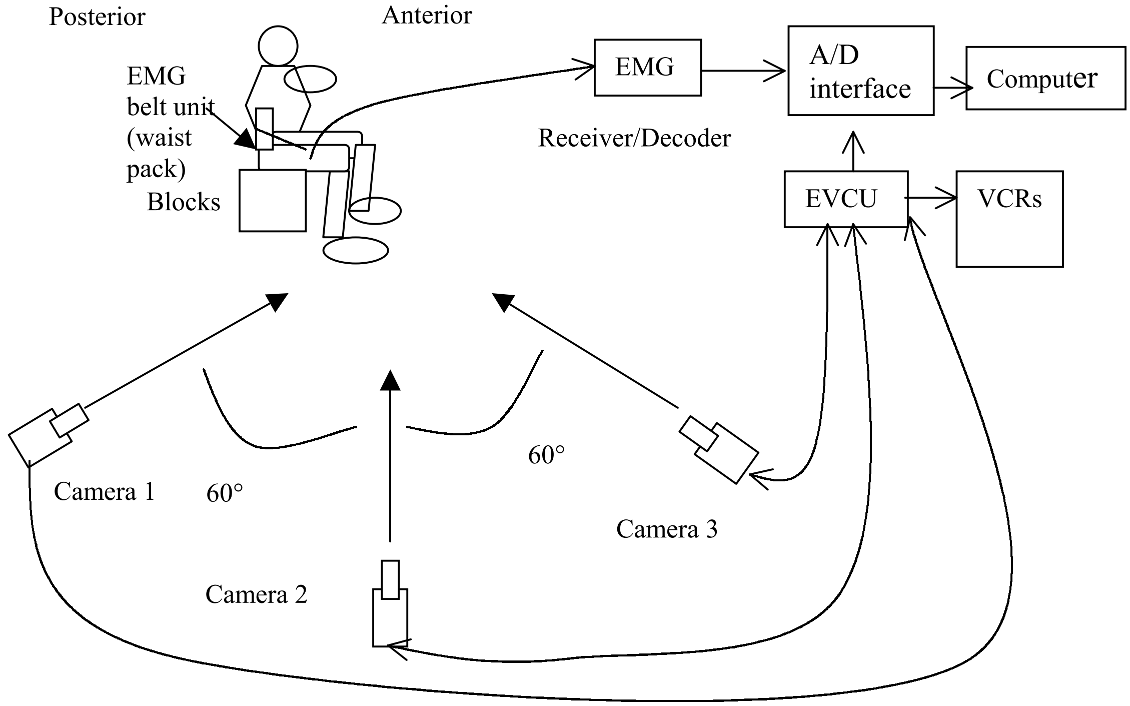


Figure 3.2. Experimental setup for the sit-to-stand task.

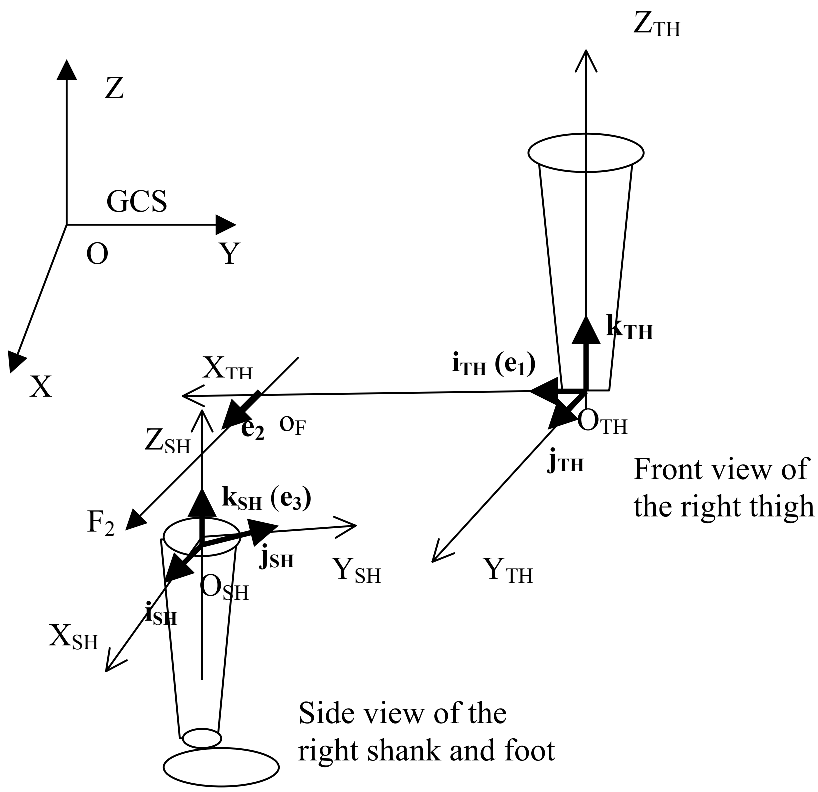


Figure 3.3. Coordinate systems. The GCS is the global coordinate system (X, Y, Z). The Anatomical segmental coordinate systems (ASCS) of the right thigh (X_{TH}, Y_{TH}, Z_{TH}) and shank (X_{SH}, Y_{SH}, Z_{SH}) are shown along with their unit vectors (<i_{TH}, j_{TH}, k_{TH}> and < i_{TH}, j_{TH}, k_{TH}>, respectively). The joint coordinate systems (JCS) of the right knee is represented by the unit vectors <e_1, e_2, e_3>. Origins of the GCS, ASCSs, and JCS of the thigh and shank are shown (O, O_{TH}, O_{SH} and O_F,), respectively.

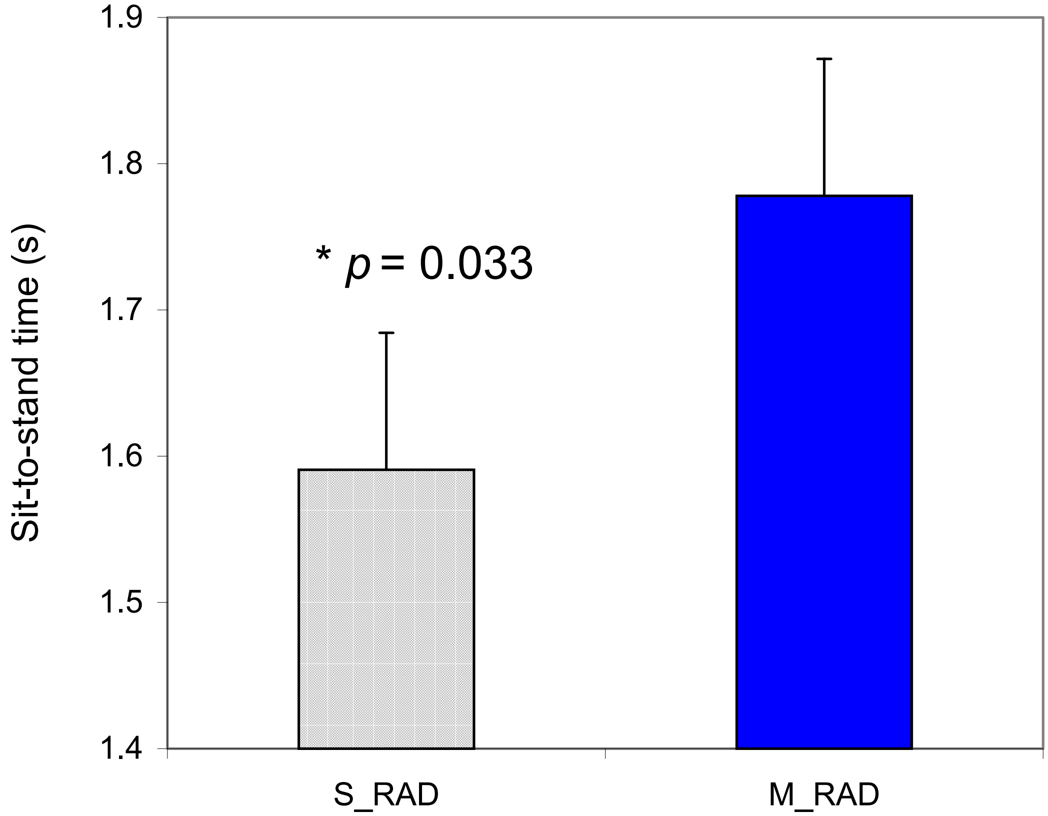


Figure 3.4. Total sit-to-stand time of the S-RAD and M-RAD groups.

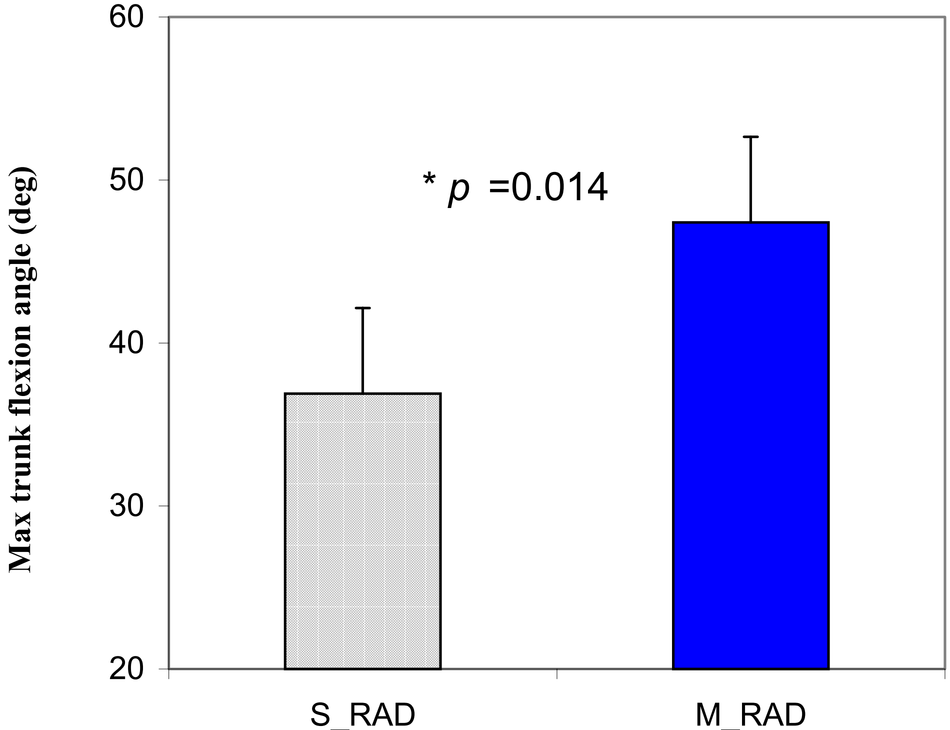


Figure 3.5. Minimum trunk flexion angle during phase I of the sit-to-stand.

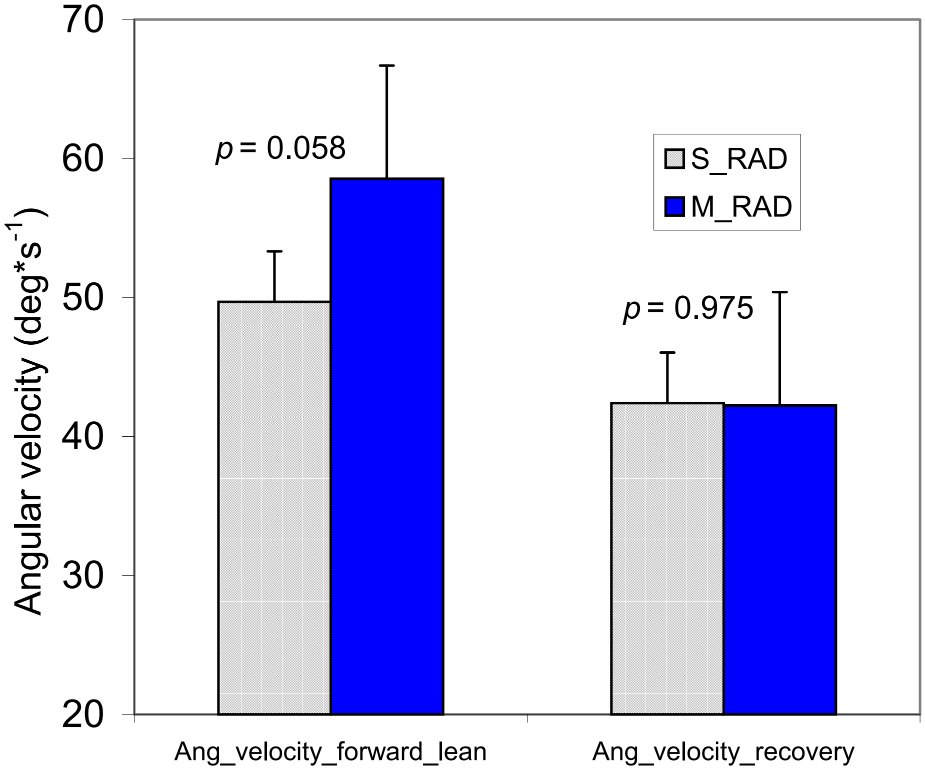


Figure 3.6. Average angular velocities of trunk flexion during Phase I and trunk extension during Phase II.

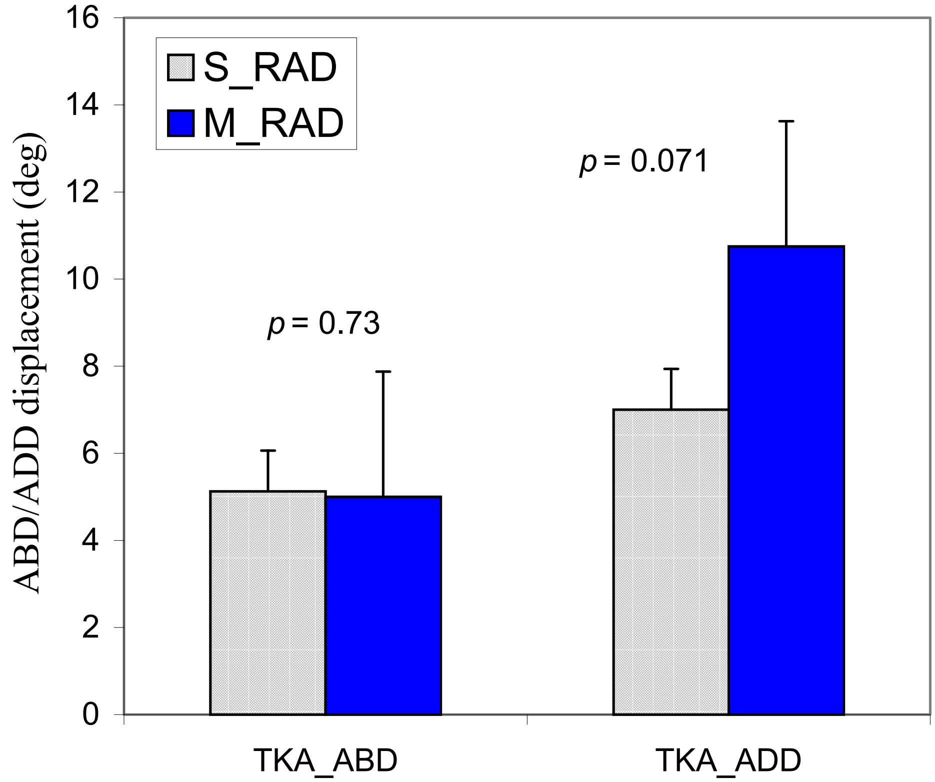
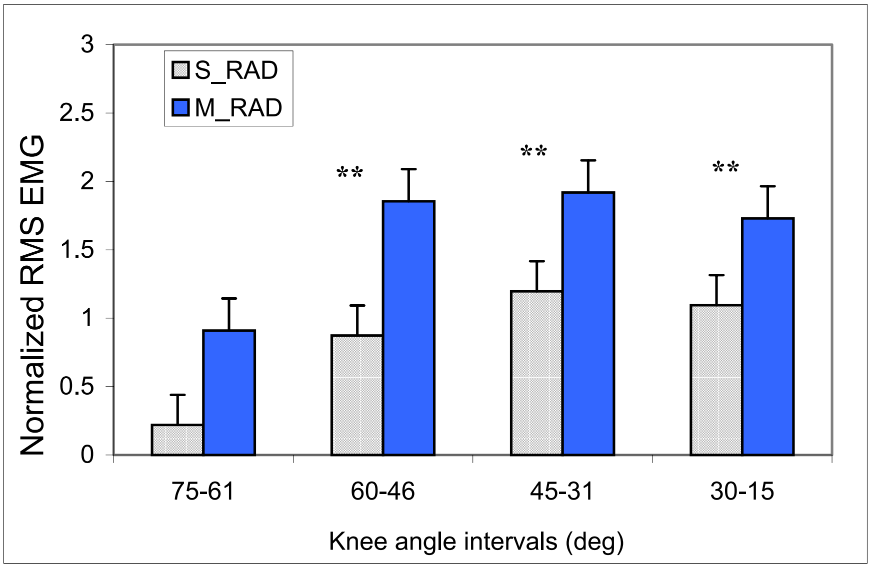


Figure 3.7. ABD and ADD displacement of S-RAD and M-RAD TKA limbs. The TKA_ABD and TKA_ADD represent the TKA limb ABD and ADD displacement, respectively.

VM



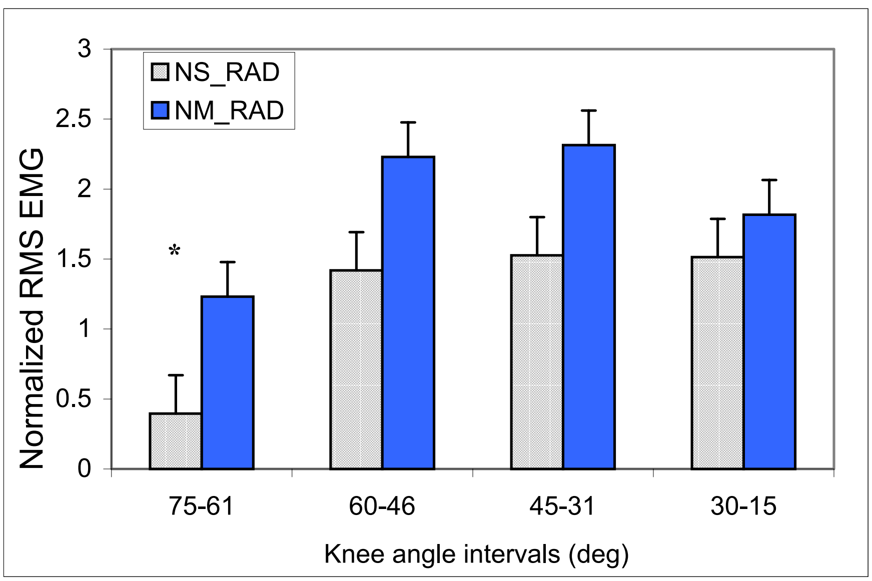
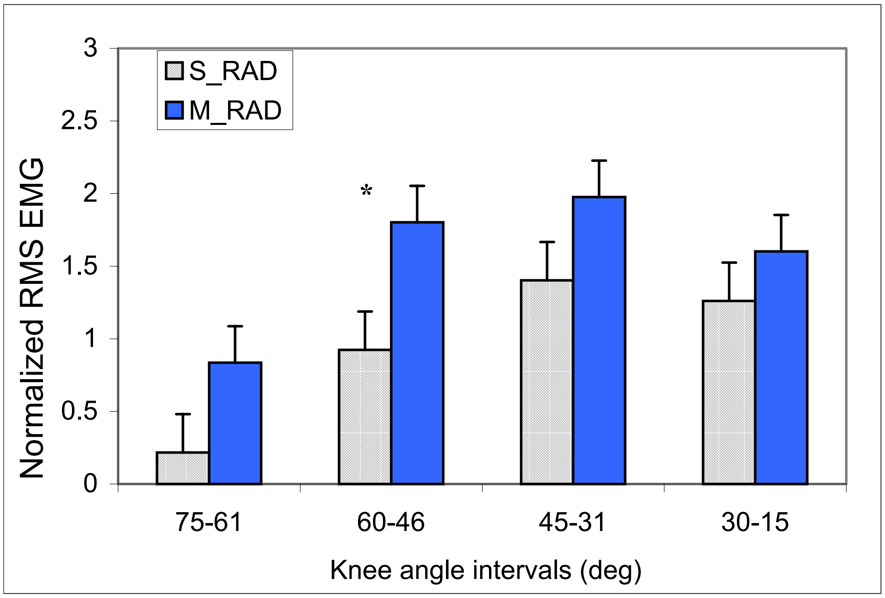


Figure 3.8. Quadriceps muscle RMS EMG for 4 angle intervals from 75 degrees to 15 degrees of knee flexion during knee extension phase of sit-to-stand movement for TKA (top) and N-TKA (bottom) limbs. VM is shown above. For comparisons between TKA groups: * indicates $p < 0.05$, ** indicates $p < 0.01$.

VL



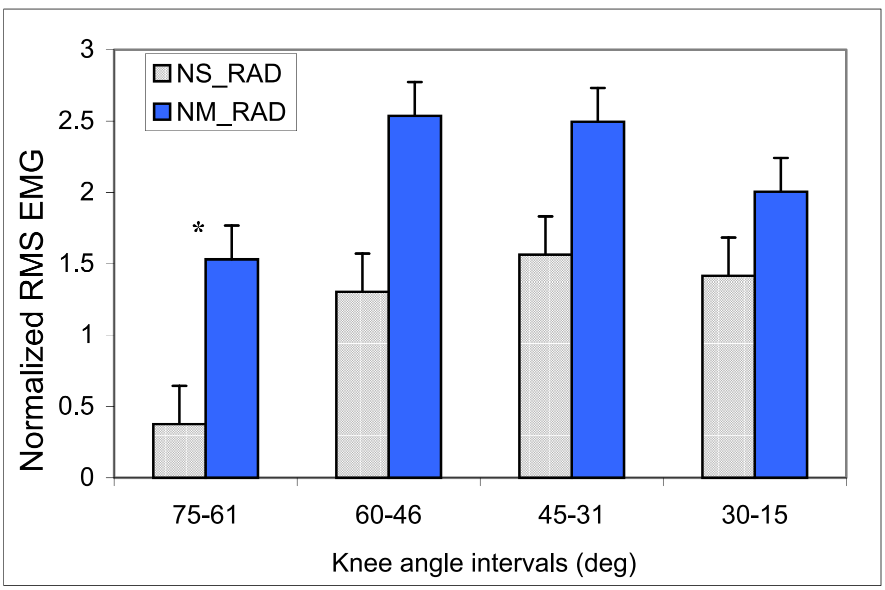
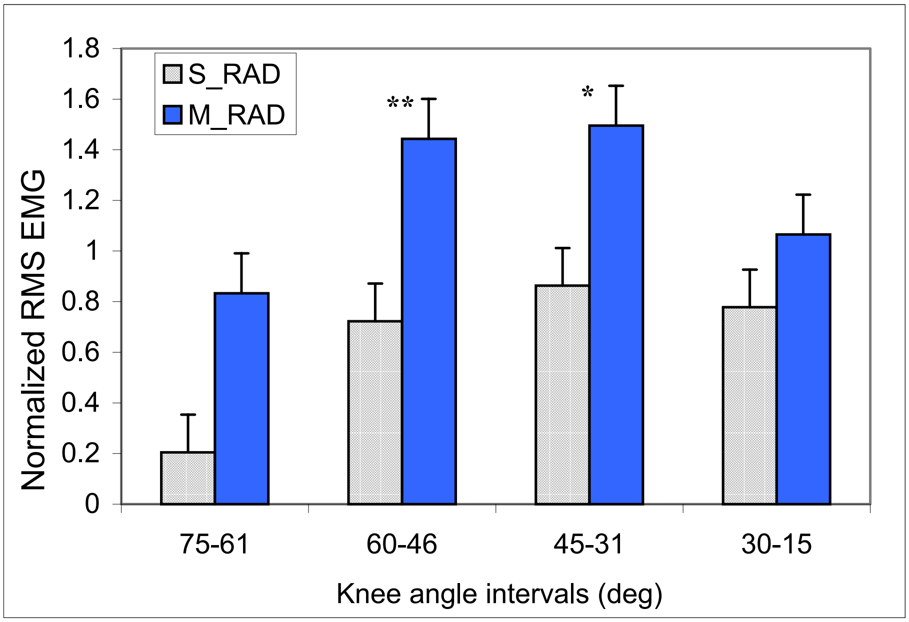


Figure 3.9. Quadriceps muscle RMS EMG for 4 angle intervals from 75 degrees to 15 degrees of knee flexion during knee extension phase of sit-to-stand movement for TKA (top) and N-TKA (bottom) limbs. VL is shown above. For comparisons between TKA groups: * indicates $p < 0.05$, ** indicates $p < 0.01$.

RF



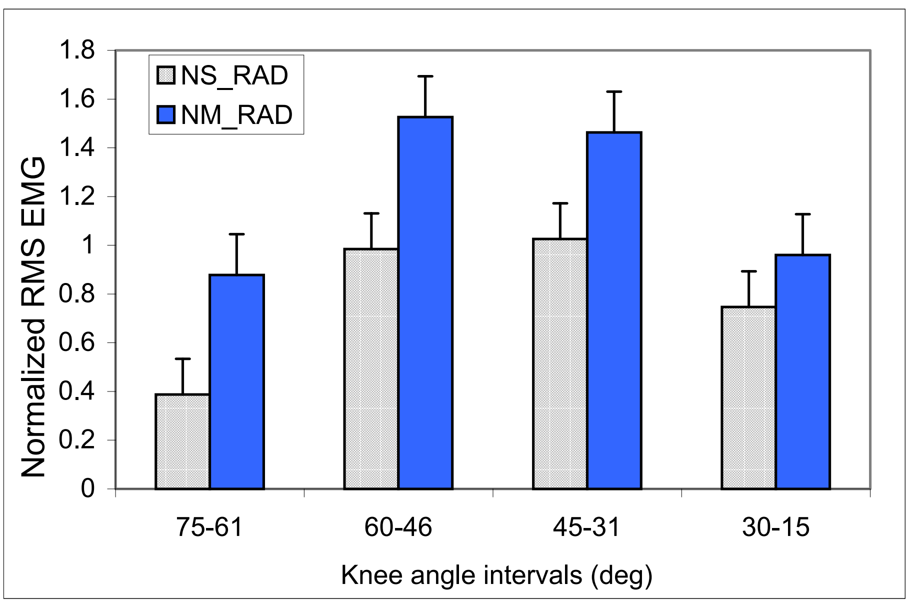
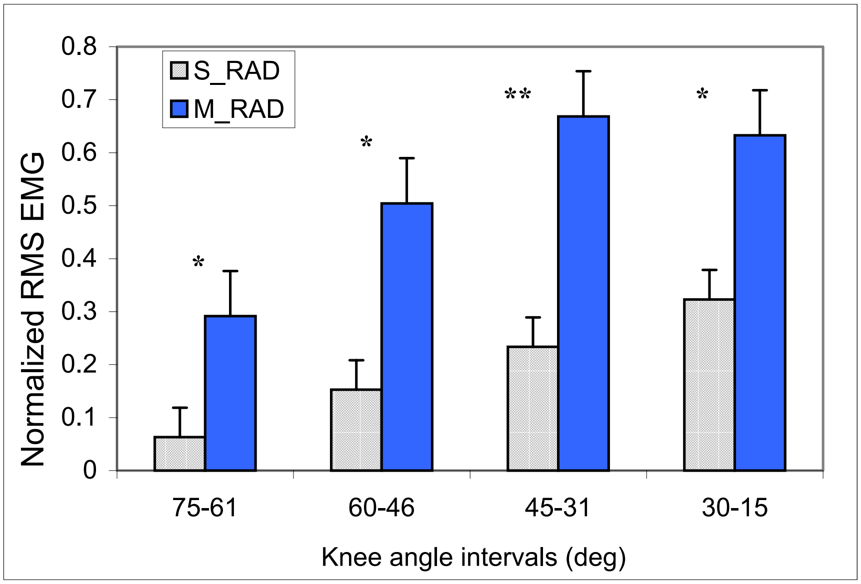


Figure 3.10. Quadriceps muscle RMS EMG for 4 angle intervals from 75 degrees to 15 degrees of knee flexion during knee extension phase of sit-to-stand movement for TKA (top) and N-TKA (bottom) limbs. RF is shown above. For comparisons between TKA groups: * indicates $p < 0.05$, ** indicates $p < 0.01$.

BF



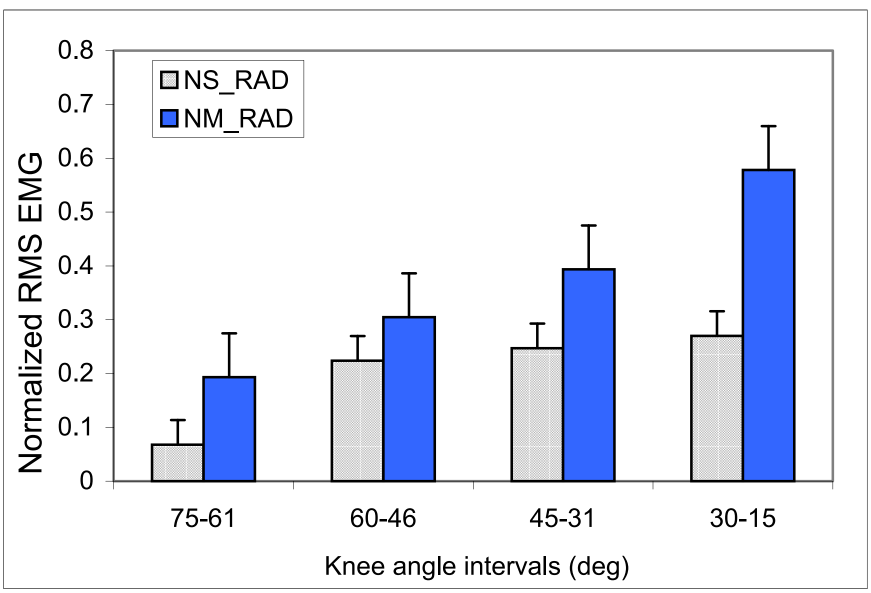
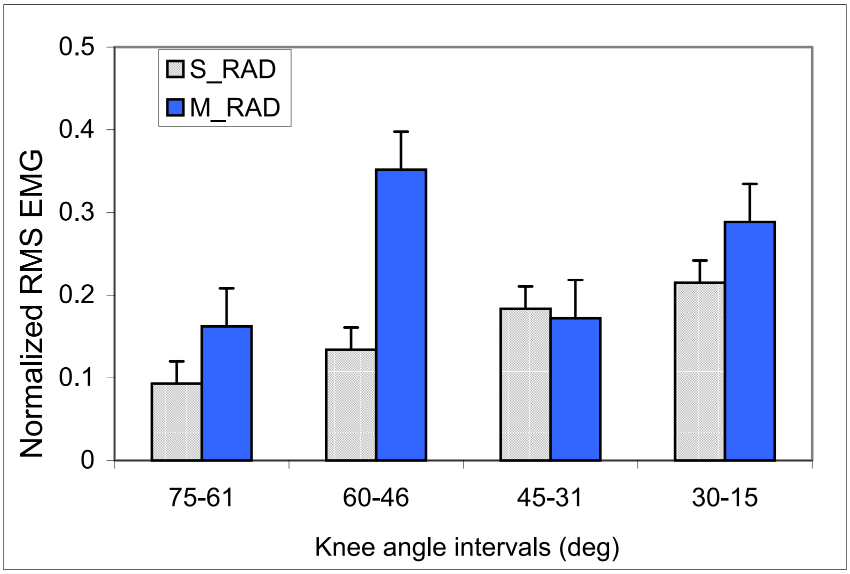


Figure 3.11. Hamstring muscle RMS EMG for 4 angle intervals from 75 degrees to 15 degrees of knee flexion during knee extension phase of sit-to-stand movement for TKA (top) and N-TKA (bottom) limbs. BF is shown above. For comparisons between TKA groups: * indicates $p < 0.05$, ** indicates $p < 0.01$.

ST



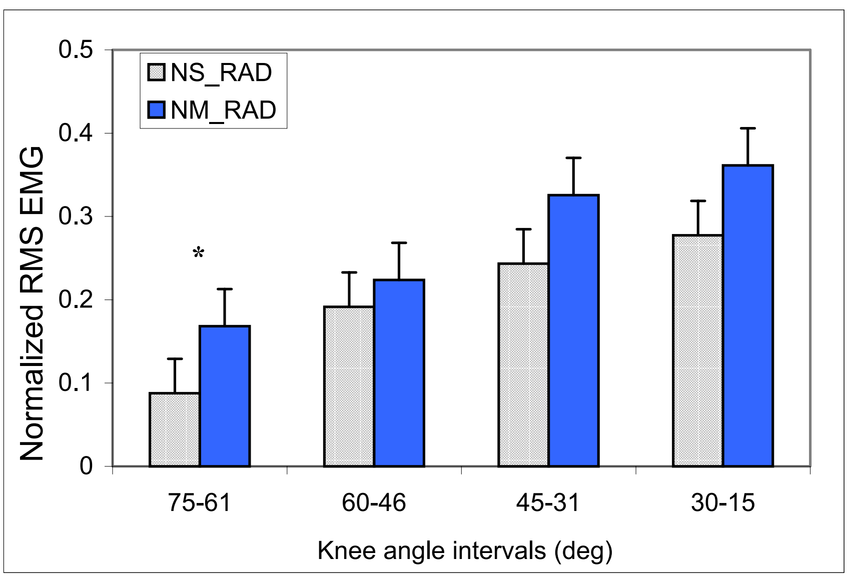


Figure 3.12. Quadriceps muscle RMS EMG for 4 angle intervals from 75 degrees to 15 degrees of knee flexion during knee extension phase of sit-to-stand movement for TKA (top) and N-TKA (bottom) limbs. ST is shown above. For comparisons between TKA groups: * indicates $p < 0.05$, ** indicates $p < 0.01$.

CHAPTER 4

A BIOMECHANICAL COMPARISON BETWEEN THE SINGLE-RADIUS AND MULTI-RADIUS TOTAL KNEE ARTHROPLASTY SYSTEMS FOR THE STAND-TO-SIT MOVEMENT[2]

[2] H. Wang, K.J. Simpson, M. Ferrara, S. Chamnongkich, S. Casto, T. Kinsey, O. M. Mahoney. To be submitted to *Journal of Biomechanics*.

Abstract

Compared to the design of a traditional multi-radius (M-RAD) total knee arthroplasty (TKA), a single-radius (S-RAD) TKA has a longer quadriceps moment arm and a fixed center of rotation in the femoral component. The purpose of this study was to investigate the effect of differences of TKA designs on knee kinematic and muscular activation for the stand-to-sit movement. Sixteen unilateral, posterior-stabilized TKA participants (8 S-RAD and 8 M-RAD) with excellent knee society scores performed 4 trials of the stand-to-sit test. Three dimensional kinematics and knee flexor and extensor electromyography (EMG) were collected during each trial. One-way ANOVA was used for statistical analyses ($\alpha = 0.05$). The M-RAD group exhibited greater TKA quadriceps EMG and hamstring co-contraction EMG than the S-RAD group. The M-RAD TKA limb demonstrated greater abduction (ABD) displacement and later ABD peak than the S-RAD TKA limb. The biomechanical differences were evident between these two TKA designs. Great quadriceps activation seen in the M-RAD group indicated great knee extension force was needed to generate necessary knee extension moment during stand-to-sit. Great ABD displacement and hamstring co-activation exhibited by the M-RAD TKA limb suggested the M-RAD TKA design could cause an unstable TKA knee. In conclusion, the S-RAD TKA could enhance the knee extension mechanism and maintain adequate knee stability during stand-to-sit activity.

Keywords: Total knee arthroplasty; Stand-to-sit; Kinematics; Electromyography

Introduction

Although implanting soft tissue (joint capsule) into the knee joints of patients with severe tibio-femoral joint deterioration began as early as 1863 (Vince, 1993; Verneuil, 1863), only since the 1950s the total knee arthroplasty (TKA) has become the standard method to treat late stage osteoarthritis and rheumatoid arthritis (Walldius, 1953; Riley, 1983). As the demand for TKA surgery doubles in the US during the next 30 years than 1997 (Freund et al., 1997; AAOS, 2000), and the trend of longer life spans continues, the wear time of a TKA implant and the physical function of the TKA limb become more significant.

The ultimate goal of a successful TKA would be to regain the functional ability necessary for the patient to perform desired physical activities and tasks for the longest wear time possible and without inducing secondary medical problems. Therefore, the arthroplasty knee should have similar mechanical characteristics as an intact knee. Thus, to allow typical knee motions and mechanics, an appropriate TKA design should replicate the locations and motions of the axes of rotation of typical knees. However, for typical knee flexion/extension (FLEX/EXT) motion, the true location and orientation of the axis is not uniformly agreed upon (Hollister et al., 1993; Frankel, 1971; Fick, 1911). Furthermore, the locations and orientations of typical knee axes are difficult to ascertain *in situ*. First, due to varying methodologies, a variety of theories exist to explain the instantaneous orientations and locations of the knee flexion/extension (KN_FLEX/EXT) axis (Zatsiorsky, 1998). Second, it has been reported that there is considerable variability among people for location, orientation and movement of the FLEX/EXT axes (Churchill et al., 1998).

To provide optimal KN_FLEX/EXT function and duration of TKA wear, TKA designs have been based primarily on the most common theories regarding the location(s) and orientation(s) of the KN_FLEX/EXT axis (Gunston, 1971; D' Lima, 2001). Until recently, for the majority of TKA designs, the "J-curve ICR" theory has been the basis for the desired KN_FLEX/EXT axis/axes. This notion is based on observations that estimated ICRs form an easily definable "J-shaped" path (when obtained from static, sagittal plane radiographs) that suggests that the FLEX/EXT axis must constantly shift during FLEX/EXT (Frankel, 1971; Fick, 1911). A variation of this idea has been used in TKA design, including the multi-ICR TKA designs of this study (S-7000™, Howmedica-Osteonics, Inc. & P.F.C.™, Johnson & Johnson Inc.). It is common that the M-RAD TKA has two or more than two ICRs in the femoral component (Hoshino, 1997) (Figure 4.1a).

The single-ICR theory is based on the premise that there is only one location for the FLEX/EXT axis, but the FLEX/EXT axis is fixed to the femur (Hollister et al., 1993; Churchill et al., 1998; Pinskerova, 2000). Hence, if the femur internally (INTN) or externally (EXTN) rotates, the FLEX/EXT axis also rotates, and no longer aligned perpendicular to an externally-fixed sagittal plane. Until recently (based on our current knowledge), the Scorpio™ Total Knee Arthroplasty System (Howmedica-Osteonics, Inc.) was the only TKA design incorporated the single-ICR theory (Figure 4.1b). In addition, although arthroplasty surgeons seek evidence to determine if the use of a single-ICR design is more beneficial to a patient than a multi-ICR design (Mahoney, 2002), little is known about the effects of the mechanical characteristics of a single-ICR design on functional benefits to the user.

The two major biomechanical differences between a traditional TKA with multiple FLEX/EXT axes (and their associated radii of rotation (M-RAD)) and a single FLEX/EXT axis TKA (and it's single radius of rotation (S-RAD)) that could lead to functional performance differences for the patient are the locations of the KN_FLEX/EXT axes. Consequently, as those FLEX/EXT ICRs of the M-RAD TKAs used in this study are more anterior than the S-RAD TKA ICR (D' Lima, 2001), it is likely that, for a given implant size, the M-RAD compared to the S-RAD TKA quadriceps moment arm is shorter, hence reducing the effective knee extensor mechanism.

Furthermore, differences for KN_FLEX/EXT axis locations between the designs are related to the radius of rotation lengths, as only the M-RAD TKA abruptly shifts from a longer to a shorter radius during KN_FLEX that may cause transitory slack of the relevant fibers of the collateral ligaments, thereby creating temporary medio-lateral knee instability. For the M-RAD TKAs used in this study, the shift from the first FLEX/EXT axis to the second FLEX/EXT axis usually occurs between 30° and 45° of knee flexion (0^o = full extension) (www.osteonics.com). This angle appears to correspond approximately to the knee angles when mid-flexion instability occurs for only M-RAD patients during knee extension movements that require raising the body (Mahoney, 1999). As the M-RAD TKA knee flexes, the FLEX/EXT axis will shift from P1, which has a longer radius of rotation (R1) to P2, which has a shorter radius of rotation (R2) (Figure 4.1a). Theoretically, this transition from R1 to R2 reduces the distance from the femoral attachments of the collateral ligaments to the tibio-femoral contact point. Consequently, collateral ligament tension also may decrease, thereby creating the mid-flexion instability at the knee joint that is often reported by M-RAD patients (Mahoney, 1999). Because the fixed FLEX/EXT axis of the S-RAD TKA results in a fixed radius of rotation (R1 in Figure 4.1b) throughout the range of knee motion, it is reasonable to expect that the collateral ligaments of the S-RAD TKA should better maintain adequate tension throughout the entire range of motion than those of the M-RAD TKA.

The stand-to-sit movement is an important common daily activity. Although sitting down is a seemingly reversed movement to standing up, the movement contributions that it requires from the actuators of the trunk, thigh, and shank segments are different from the sit-to-stand. Furthermore, the roles of the knee extensor and flexor muscles are different between the two movements, i.e. the quadriceps act eccentrically to provide enough knee extension torque in order to control the descending motion during the stand-to-sit rather than providing force to rise the body upwards. In addition, the ability to balance the body posture and maintain the stabilization of the knee joints is important when descending the body without hand assistance. After reviewing the literature, only a few studies focusing on the stand-to-sit movement (KralJ et al., 1990; Kerr et al., 1997). Unfortunately, there is no information about the knee joint kinematic characteristics during the stand-to-sit. In addition, very little is known about the influence of the TKA design on the functional performance and muscle activation of the stand-to-sit.

Therefore, the purpose of this study was to investigate how the designs of the S-RAD and M-RAD TKA affect the knee joint kinematics and activation of knee muscles during stand-to-sit.

As the differences in the number of axes and their locations between the M-RAD and the S-RAD TKAs were thought to affect muscle moment arms and collateral ligament tension, we hypothesized that the S-RAD TKA limb would have lesser normalized quadriceps EMG, hamstrings EMG, and ABD/ADD angular displacement than the M-RAD TKA limb for the stand–to-sit movements. We further hypothesized that the S-RAD TKA group would have less descent time and less trunk flexion than the M-RAD TKA group.

Methods

Participants

Sixteen individuals participated in this study. Eight of the individuals had a unilateral S-RAD TKA (Scorpio™ PS, Howmedica-Osteonics, Inc.). The remaining eight individuals had a unilateral M-RAD TKA (S-7000™ PS, Howmedica-Osteonics, Inc.; P.F.C. ™ PS Johnson & Johnson, Inc.). Table 4.1 shows other participant characteristics. All the TKA surgeries were performed by the same surgeon. Participants were prescreened based on the following criteria of having:

- No history of stroke, heart or diabetes, or other major diagnosed health problems.
- The TKA surgery at least 18 months prior to the study.
- Medical clearance from his or her physician to participate in the study.
- No history of taking any drug that had the potential to adversely affect performance.
- No hip, knee, ankle and low back pain.
- Scores greater than 90 on the Clinical and Function subsections of the Knee Society Clinical Rating System (Appendix A) (Insall, et al. 1989).

- Passive knee flexion ROM values greater than 100° for both limbs.

Instrumentation and Experimental Setup

Instrumentation

A Peak Motion Measurement System™ (Peak Performance Technologies, Inc) was used to collect the kinematic data, that include: three genlocked high-speed video cameras (Pulnix™, Model TM640) with a sampling rate of 120 Hz and a shutter speed of 1/1000 s; three S-VHS VCRs (JVC™, Model BR-5378U); Peak Performance™ 21-point calibration frame (2.2185 × 1.583 × 1.5035 m^3); Peak Performance™ event video control unit (EVCU) and 16 channel A/D interface; and Peak Motus™ V. 4.3.1 software package. Two sets of different sizes reflective markers (diameter = 2.0 cm and 1.2 cm, respectively) were used.

A 16-channel MYOPAC™ EMG system (Run Technologies, Inc.) was used to collect the differential input surface electromyographic (EMG) signals of the vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF) and semitendinosus (ST) during stand-to-sit tests. Disposable electrodes (Blue Sensor™, Medicotest, Inc.) were used to collect the EMG signals. The average inter-electrode distance was 2.5 cm. A reference ground electrode was attached over the distal radius of the wrist. The EMG signal (sampling rate =1080 Hz) from the electrodes was sent to a waist pack and amplified (gain = 1000 to 10,000), then transmitted to a receiver and amplifier (MPRD-101 Receiver/Decoder unit) (CMRR = 110 dB) via an optical fiber cable. The analog EMG signal from the receiver was digitally transformed via a 12-bit A/D board.

A KIN-COM III™ isokinetic dynamometer (500 Hz) (Chattecx Corp, USA) was used for conducting isometric strength testing for knee extensor and flexor muscles in order to obtain the EMG of the VM, VL, RF, BF, and ST during maximal voluntary contraction (MVC).

Three wood blocks with different heights (10 cm, 20 cm and 30 cm) were used for the participants to sit upon during the stand-to-sit tests.

Experimental Setup

The placements of the three cameras are illustrated in Figure 4.2. Video signals of the three cameras and the EMG were synchronized through the EVCU.

The participant's body was tested from side to side. The EMG electrodes and reflective markers were placed only on the tested side. After placing the EMG electrodes on the participant, reflective markers were placed on the tested side of the body. Two configurations of reflective markers, dynamic (DYN) and anatomical (ANA) were used (Table 4.2). Some markers were served as both DYN and ANA markers. The purpose of the ANA markers during kinematic data reduction were to establish the unit vectors for the segmental coordinate systems of shank and thigh, while the DYN markers were used during data reduction to reconstruct the location of ANA markers. Thus, for each segment, DYN and ANA markers locations were captured when the participant was standing quietly before data collection of the actual stand-to-sit trials, while only the locations of DYN markers were captured during data collection.

Protocol

- A consent form (Appendix B) was signed by the participant.
- A pretest questionnaire was administered (Appendix C).
- The participant's body mass, body height, and lower leg length were measured.
- Five-minute low intensity bicycling on a stationary cycling ergometer was performed as a warmup.
- Passive hip and knee joint stretching were performed with the assistance of a certified athletic trainer.
- The maximum knee extension and flexion angles were measured by the athletic trainer.
- The stand-to-sit tests were administered.
- The strength test was administered.

- The posttest questionnaire (Appendix D) was conducted to obtain participant's perceptions of the quality of his/her physical functioning in order to qualitatively assess his/her satisfaction with the TKA.

<u>The General Protocol for the stand-to-sit tests</u>

- The height of the blocks was adjusted so that the participant could sit on the block comfortably with both thighs parallel to the floor at approximately 90° of knee flexion.
- The right side of the body was tested first. In order to capture the locations of all the ANA and DYN markers on the shank and thigh to establish the relationship between ANA and DYN markers, the participant was videotaped for 10 sec. while standing quietly.
- In order to obtain the reference angular displacements in the three directions (FLEX/EXT, ABD/ADD, and INT_R/EXT_R) between the femur and the tibia for further calculating the change of angular displacement of the knee joint, the participant was videotaped for 10 sec. while she/he is standing naturally.
- In order to obtain a baseline value for future EMG data processing, the participant sat quietly and relaxed on blocks while three sec. of EMG data were collected.
- For the actual stand-to-sit task, the participant sat on the blocks with arms across the chest, and the feet were placed shoulder width apart on the floor. To perform one trial, after the tester gave a verbal signal, the participant stood up as rapidly as possible and maintained the standing position for five sec. To ensure collecting a good trial (the participant stood up by himself/herself without losing balance), a total of four trials were administered before repeating the protocol for the other limb.
- After testing one leg, the participant took a 5-min. rest. During this period of time, reflective markers and the EMG electrodes were placed on the other leg. Then the participant was instructed to turn around 180° for data collection of the other leg.

- After finished stand-to-sit tests, isometric strength tests were conducted. The N-TKA limb was tested first. Prior to strength tests, baseline EMG signals were collected for three sec. while the participant maintained a relaxed position for the test limb.
- Isometric strength tests were administered at 60° for knee extensor and 30° for knee flexor. EMG data of the VM, VL, RF, BF and ST were collected during isometric strength tests. The isometric EMG data were used for normalizing the EMG signals during the stand-to-sit tests.

Data Reduction

EMG data reduction

EMG data were divided by the gain factors that were used to magnify the EMG signal during data collection and adjusted to the baseline value. Rectified EMG values were expressed as a percentage of the mean rectified EMG obtained during the maximal effort isometric tests. Using the normalized rectified EMG, root mean squared (RMS) data were generated as follows:

$$RMS = \{1/T \int_0^T (rEMG(t))^2 dt\}^{1/2},$$

where rEMG(t) represented the rectified EMG at time t, dt was the sampling rate (1/1080 s.), and T was the moving window size of 0.026 s. (28/1080 s.). The mean of the normalized RMS_i was calculated for each of the four angular intervals (15°-30°, 31°-45°, 46°-60°, and 61°-75°) (RMS_i, where i represented the specific angle interval).

Kinematic data reduction

Peak Motus™ 4.3.1 software was used to track the marker locations for each camera and to reconstruct the three dimensional coordinates of these markers by using the Direct Linear Transformation (DLT) method (Peak Motus™ manual, 1998). The raw data were then smoothed using a Quintic Spline method (Jackson, 1979).

There was a three-part process to derive the knee joint angles demonstrated during the actual stand-to-sit trials (see Appendix E for detail). First, the data collected when the participant stood with the ANA and DYN markers presented (see Table 4.2 for their locations) were used to construct an anatomical segment coordinate system (ASCS) and a dynamical segment coordinate system (DSCS) for each segment (thigh and shank). The relationship between the ASCS and DSCS was represented by a transformation matrix. Therefore, during the actual stand-to-sit trials, the location of the ASCS of each segment could be obtained through the current DSCS location and the transformation matrix.

Second, a knee joint coordinate system (JCS) to describe the relative motions between the thigh and shank segments was established based on the ASCS of both segments (Grood & Suntay, 1983). As shown in Figure 4.3, the unit vectors $\mathbf{e_1}$, $\mathbf{e_2}$, and $\mathbf{e_3}$ established the JCS of the knee. $\mathbf{e_1}$ and $\mathbf{e_3}$ were the unit vectors along the medio-lateral axis of the thigh (X_{TH}) and the longitudinal axis of the shank (Z_{SH}), respectively, where the X_{TH} was the X-axis of ASCS of the thigh and Z_{SH} was the Z-axis of ASCS of the shank. Therefore, $\mathbf{e_2}$ was the unit vector of the floating axis F_2:

$$\boldsymbol{e_2} = (\boldsymbol{e_3} \times \boldsymbol{e_1})/|\, \boldsymbol{e_3} \times \boldsymbol{e_1}|$$

Third, the knee angles for each of the three angular directions (FLEX/EXT, ABD/ADD, and INT_R/EXT_R) during the stand-to-sit actual trials were expressed relative to the corresponding natural standing knee angles (Grood & Suntay, 1983). Table 4.3 shows the calculations of these angles.

In addition, min and max of INT_R/EXT_R and ABD/ADD angles were calculated. Percentage time reaching the min and max of INT_R/EXT_R and ABD/ADD angles were generated. The displacements of EXT_R/INT_R and ABD/ADD during the stand-to-sit were also generated.

In addition, the hip flexion angle was defined as the angle between the connection line of iliac spine and great trochanter and the longitudinal axis of the thigh (Z_{TH}). The trunk forward lean angle was defined as the angle between the connection line of iliac spine and acromion and the antero-posterial horizontal line. The thigh and shank inclination angles were defined as the angles between the antero-posterial horizontal line and the longitudinal axes of thigh (Z_{TH}) and shank (Z_{SH}), respectively.

The total stand-to-sit time was calculated from the beginning of the trunk movement to the end of the trunk movement. Furthermore, the maximum trunk flexion, average angular velocity of trunk flexion, maximum hip flexion, max shank flexion, and percentage time reaching the above critical events were generated.

Statistical Analysis

The relative knee INT_R, EXT_R, ABD, and ADD displacements, maximum and minimum shank, thigh, trunk, and hip angles during the stand-to-sit tests were selected as dependent kinematic variables. The times to these critical events relative to the stand-to-sit movement time (% TOT_T) were also selected. The normalized RMS EMG of the VM, VL, RF, BF, and ST for the four equal angle intervals (15°-30°, 31°-45°, 46°-60°, 61°-75°) during stand-to-sit tests were selected as dependent EMG variables.

Statistical analyses were performed using SPSS™ (V.10, Chicago, IL). As shown in Table 4.1, the age and post-operation time were statistically significant between the two TKA groups. One-way ANCOVAs were used to test if the age and post-operation time could be significant effects to the kinematic and EMG variables. We found that, for 54 dependent variables, there were one interaction and one significant effect related to age factor. Also, there were three significant effects related to post-operation time. The type I error might account for the small number of significant effects brought by the age and post-operation time. Based on these findings, it was concluded that the age and post-operation time had very limit effect on the kinematic and EMG variables. Thus, one-way ANOVAs were used to determine the differences between the S-RAD and M-RAD TKA groups for the kinematic and EMG variables. The significance level was $\alpha = 0.05$ for all statistical tests.

Results

For participant characteristics (Table 4.1), the TKA groups exhibited two significant differences. The S-RAD group (65 ± 5 yr.) was 7 years younger and had undergone surgery (29 ± 11 mo.)more recently than the M-RAD group (72 ± 7 yr. and 79 ± 25 mo., respectively). However, there were no statistical differences of body height, body mass, clinical and functional knee scores, and TKA range of motion between the two groups.

Appendix F shows the samples of kinematic graphs of the stand-to-sit. The kinematics of the stand-to-sit movement was divided into two phases: Phase I, knee flexion phase (i.e., from the initial movement to the cessation of knee flexion), and Phase II, trunk extension phase, (i.e., from the max trunk flexion to the end of trunk extension). The results were reported as follows: a) FLEX/EXT kinematics, b) the knee joint kinematics, and c) the lower extremity EMG.

As shown in Table 4.4, there were no statistical differences for any FLEX/EXT variables between the S-RAD and M-RAD groups. However, the Figure 4.4 shows that the M-RAD group tended to use more time (1.98 s) to sit down than the S-RAD group (1.79 s) ($p = 0.084$). Both groups' minimum hip flexion angle occurred after the minimum trunk flexion. Though non-statistically significant ($p > 0.05$), due likely to interparticipant variability, the S-RAD group tended to reach peak angles prior to the M-RAD group, for example, percentage time to maximum shank flexion (46 % TOT-T and 55 % TOT-T for S-RAD and M-RAD groups, respectively, $p = 0.195$).

Differences between the TKA limbs of the groups were evident for the ABD/ADD variables (Figures 4.5 – 4.7). The M-RAD TKA limb reached its local ABD peak at 52 % TOT-T, significantly later ($p = 0.028$) than the S-RAD TKA limb (33 % TOT_T). Also, the M-RAD TKA limb tended to reach its local ABD peak at a greater knee flexion angle (57º) than the S-RAD TKA limb (42º) ($p = 0.065$). Furthermore, the M-RAD TKA limb demonstrated greater ($p =$

0.041) ABD displacement (10º) than the S-RAD TKA limb (5º), but tended to have less (p = 0.065) ADD displacement (3º) than the S-RAD TKA limb (6º).

Figures 4.8 – 4.12 show the EMG results of the quadriceps and hamstring muscles, respectively for both limbs and both TKA groups. The M-RAD TKA limb exhibited greater ($p < 0.05$) VM EMG than the S-RAD TKA limb at the knee FLEX angle intervals of 31º - 45º and 61º - 75º, and a tendency to have greater VL EMG for all knee FLEX angle intervals (p values range from 0.057 to 0.087). In addition, the M-RAD compared to the S-RAD TKA limb demonstrated greater ($p < 0.05$) BF co-contraction EMG for all knee FLEX angle intervals. For the N-TKA limbs, the M-RAD group demonstrated greater activation ($p < 0.05$) than the S-RAD group for VM and RF, from 30º to 75º and 60º to 75º of knee flexion, respectively.

Discussion

The primary question of this study is: are there biomechanical differences that are functionally significant between the M-RAD and S-RAD TKA groups due to the differences in the TKA designs? As there are two major design differences between the M-RAD and S-RAD TKAs, we will discuss the functional effects of different quadriceps moment arm lengths and the change in radius length for the M-RAD TKA that does not occur during KN_FLEX/EXT with an S-RAD TKA.

Functional Differences Due to the Differences of Moment Arm Length between TKA Types

As we mentioned earlier, the S-RAD TKA limb had a longer quadriceps moment arm than the M-RAD TKA limb. All else being equal, participants with an S-RAD TKA should be able to generate the necessary knee extensor muscle moment with relatively less knee extension force than the M-RAD TKA participants. From another viewpoint, if the M-RAD group could not generate more quadriceps force than the S-RAD group, then this group would display compensatory adaptations to help perform the stand-to-sit movement. Furthermore, if the M-RAD group increased the generation of the quadriceps force, the quadriceps would display high magnitude EMG. Therefore, in this section, we will focus on compensatory adaptations and quadriceps EMG activity.

Compensatory adaptations

Compensatory adaptations were demonstrated by the M-RAD group in a recent sit-to-stand study (Wang et al., 2002). In the current study, we only found that the M-RAD group tended to use more time to sit down than the S-RAD group ($p = 0.084$). However, we could not find any evidence related to the compensatory adaptation, because there were no statistical difference of trunk flexion angle, trunk flexion and extension velocity between the two TKA groups. The possible explanation is that the stand-to-sit movement does not require great amount of knee extension torque like the sit-to-stand movement to counteract the gravity effect. Thus, compensatory adaptations are not necessary for the M-RAD group during stand-to-sit movement.

Quadriceps EMG

During the stand-to-sit, the quadriceps contracts eccentrically in order to counteract the flexion torque and ensure the body has a comfortable touchdown on the chair. In the current study, we found that the M-RAD TKA limb had or tended to have greater VM and VL EMG than the S-RAD TKA limb. Great quadriceps eccentric EMG increased the knee extension force and therefore increased the knee extension torque. As the M-RAD TKA limb had a shorter quadriceps moment arm than the S-RAD TKA limb, all else being equal, the M-RAD TKA limb would use greater quadriceps eccentric contraction to generate necessary knee extension torque. In addition, the N-TKA limb of the M-RAD group demonstrated greater VM and RF eccentric EMG than those of the N-TKA limb of the S-RAD group. The possible explanation is that, the M-RAD group also tried to increase the effort of the intact limb to compensate the relatively weak TKA limb due to the disadvantage of the short moment arm in the TKA.

Mid Flexion Instability

Knee mid flexion instability were found in the M-RAD participants in a recent sit-to-stand study (Wang et al., 2002). As the knee flexed during the stand-to-sit movement, we expected that the M-RAD group would also experience an unstable TKA limb in the medio-lateral direction due to the change of the radii in femoral component. In this section, we will discuss the effect of design difference of one radius vs. two or three radii between the S-RAD and M-RAD TKAs on the knee kinematics and hamstring co-activation of the TKA limb, respectively.

Knee ABD/ADD kinematics

As we expected, the M-RAD TKA limb demonstrated 5 deg more ABD displacement than the S-RAD TKA limb. Also, the M-RAD TKA limb reached the peak ABD much later (17% more of the total stand-to-sit time and 15 deg more knee flexion) than the S-RAD TKA limb. These findings suggested that the M-RAD TKA limb could not effectively control medio-lateral stability when the knee flexion angle increased. The possible explanation is, when the M-RAD TKA limb started using the short radii in the femoral component, the tension of the collateral ligaments was reduced. Thus, the M-RAD TKA limb could allow the ABD motion to grow until the medial collateral ligament regained its tension. However, the single radius design of the S-RAD TKA could maintain the collateral ligament in proper tensioning during knee flexion, so that the S-RAD TKA limb exhibited less ABD displacement and an earlier ABD peak than the M-RAD TKA limb.

Interestingly, after the ABD displacement, the M-RAD TKA limb demonstrated 3 deg less ADD displacement than the S-RAD TKA limb. Without having adequate tension, the medial collateral ligament of the M-RAD TKA could not have the ability to pull the TKA knee from the peak ABD back to the normal position like the S-RAD TKA did.

Hamstring co-activation EMG

The M-RAD TKA limb not only displayed greater ABD displacement, but also greater BF co-contraction EMG than the S-RAD TKA limb during stand-to-sit. Hamstring muscle group could have three functions during the stand-to-sit movement. First, the hamstring could extend the hip joint and flex the knee joint (Thompson, 1989). Second, the hamstring could assist the ACL to resist the tibia anterior shear (Baratta et al., 1988; Kasman, 1998). Third, hamstring co-contraction could improve the knee joint stability in the medio-lateral direction (Zhang et al., 2001; Wang et al., 2002). As both TKA groups showed similar trunk FLEX/EXT kinematics, the contribution of the hamstrings to the trunk extension might be at the same level for both TKA groups. Also, a previous study showed that the TKA limb had less BF co-contraction than N-TKA limb (Wang et al., 2001). The geometry of the PS TKA design could fully replace the ACL and PCL functions. Therefore, in the current study, the increasing BF co-activation seen in the M-RAD TKA limb indicated the need of a stabilization mechanism in the medio-lateral direction for TKA limb during stand-to-sit. By increasing the co-contraction level, the BF could tighten and strengthen the knee joint. On the contrary, the S-RAD TKA showed less BF co-contraction due to the fact that the tensions of collateral ligaments were well maintained.

In summary, the M-RAD TKA limb increased the quadriceps eccentric contraction in order to provide adequate knee extension moment during the stand-to-sit. Also, the M-RAD TKA limb exhibited an unstable knee by showing greater ABD displacement and BF co-contraction than the S-RAD TKA limb.

In conclusion, compared to the M-RAD TKA design, the S-RAD TKA design could enhance the knee extension ability and benefit the collateral ligaments to stabilize the knee joint during the stand-to-sit activity.

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Table 4.1. Means and standard deviations for participant characteristics.

Variables	TKA group S-RAD (n = 8)	TKA group M-RAD (n = 8)
Gender		
Number of male	4	6
Number of female	4	2
TKA type	Scorpio^{TM} PS	S-7000^{TM} PS (n = 4) P.F.C^{TM} PS (n = 4)
Age (yr.)	65 ± 5 *	72 ± 7
Post operation time (mo.)	29 ± 11 *	79 ± 25
Body height (m)	1.71 ± .10	1.72 ± .07
Body mass (kg)	94 ± 14	89 ± 15
Clinical knee society score	95 ± 2	96 ± 2
Functional knee society score	95 ± 8	90 ± 11
TKA Knee range of motion (deg)	110 ± 7	113 ± 8

Note. * indicates significant comparison between the TKA groups (critical $F^*_{1, 14} = 4.60$; $p < 0.05$)

Table 4.2. The DYN and ANA markers' placements

Marker's Title	Description of location	Type of markers
Shoulder	Acromion	DYN
Waist	Lateral iliac spine	DYN
Great trochanter	The center of the great trochanter	ANA & DYN
Mid thigh	Anterior mid thigh	DYN
Lateral epicondyle	Center of lateral femoral epicondyle	ANA & DYN
Medial epicondyle	Center of medial femoral epicondyle	ANA
Proximal anterior shank	2 cm above the center of the tibial tuberosity	ANA & DYN
Distal anterior shank	Anterior side of the shank and 5 cm above the center of the lateral malleolus	ANA & DYN
Rear distal shank	Rear side of the shank and 5 cm above the center of lateral malleolus	ANA & DYN
Lateral malleolus	Center of the lateral malleolus	DYN
Heel	2 cm below and 2 cm posterior the center of lateral malleolus (on calcaneus)	DYN
The 5^{th} metatarsal head	Lateral edge of head of fifth metatarsal	DYN

Table 4.3. The knee flexion/extension (FLEX/EXT), abduction/adduction (ABD/ADD), and internal/external (INT_R/EXT_R) rotation angles (Grood & Suntay, 1983)

Angle	Right knee	Left knee
FLEX(-)/EXT(+) angle	$\arccos(\mathbf{e_2} \bullet \mathbf{k_{TH}}) - \pi/2$	$\arccos(\mathbf{e_2} \bullet \mathbf{k_{TH}}) - \pi/2$
ABD(+)/ADD(-)	$\arccos(\mathbf{e_1} \bullet \mathbf{e_3}) - \pi/2$	$\pi/2 - \arccos(\mathbf{e_1} \bullet \mathbf{e_3})$
INT_R(-)/EXT_R(+)	$\pi/2 - \arccos(\mathbf{i_{SH}} \bullet \mathbf{e_2})$	$\arccos(\mathbf{i_{SH}} \bullet \mathbf{e_2}) - \pi/2$

Note. See Figure 4.3 for explanation of unit vectors

Table 4.4. Means and standard deviations of times to peak angles. No significant differences existed between the TKA groups (% TOT-T).

	t Maximum trunk flexion	t Maximum hip flexion	t Maximum shank flexion
S-RAD group	52 ± 4	61 ± 6	46 ± 15
M-RAD group	54 ± 7	65 ± 9	55 ± 10

Note. * indicates significant comparison between the TKA groups (critical $F^*_{1, 14} = 4.60$; $p < 0.05$)

a) b)

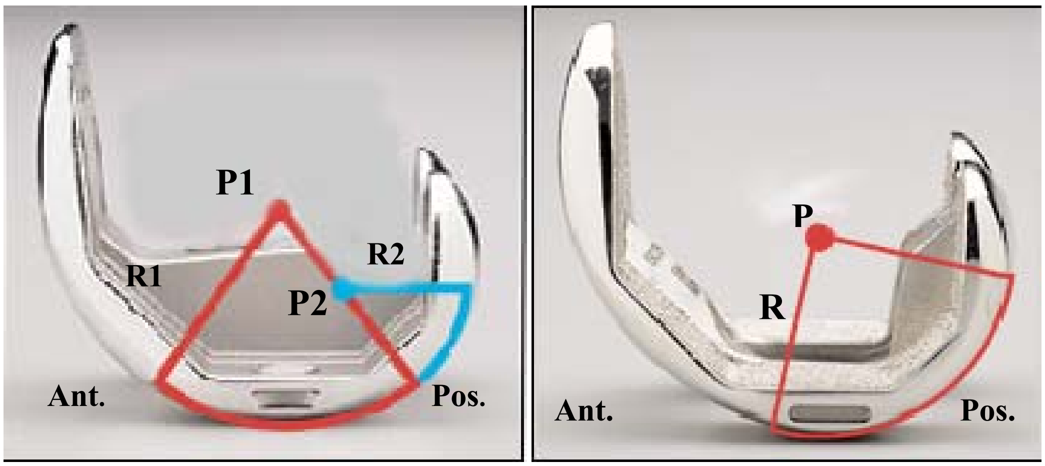


Figure 4.1. Lateral views of left knee femoral components of the a) M-RAD TKA and b) S-RAD TKA. P1, P2, and P represent the centers of flexion/extension rotation, and R1, R2, and R represent the corresponding radii of rotation. (Courtesy of Stryker-Howmedica-Osteonics, Inc.)

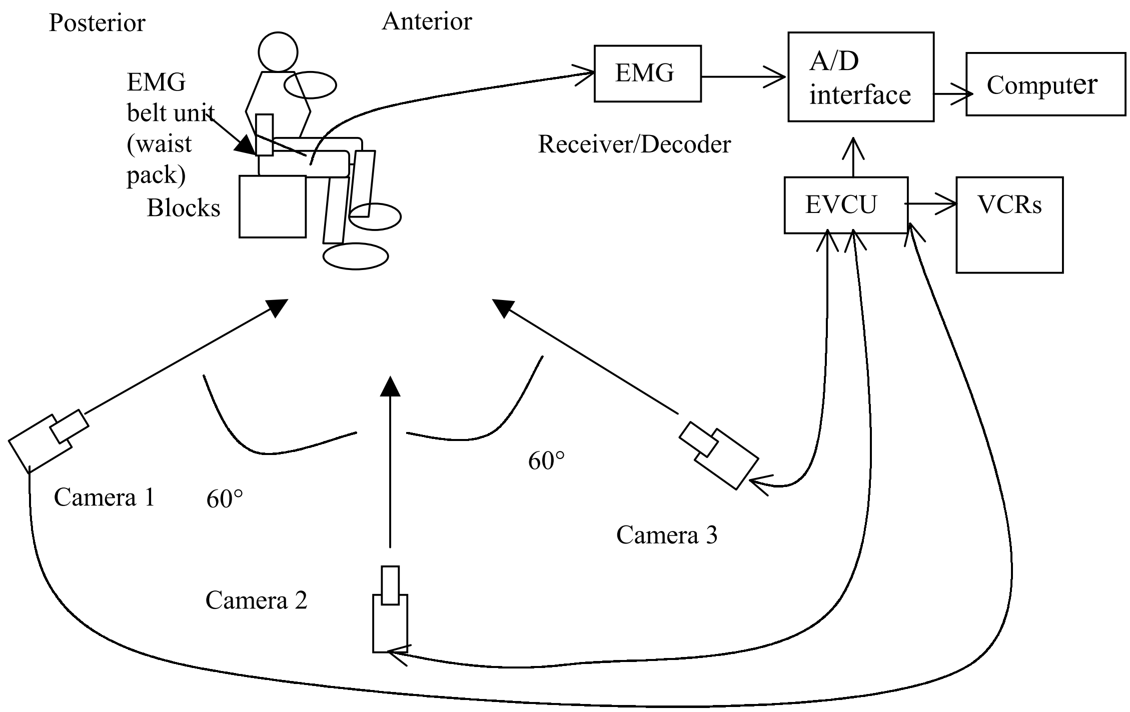


Figure 4.2. Experimental setup for the stand-to-sit task.

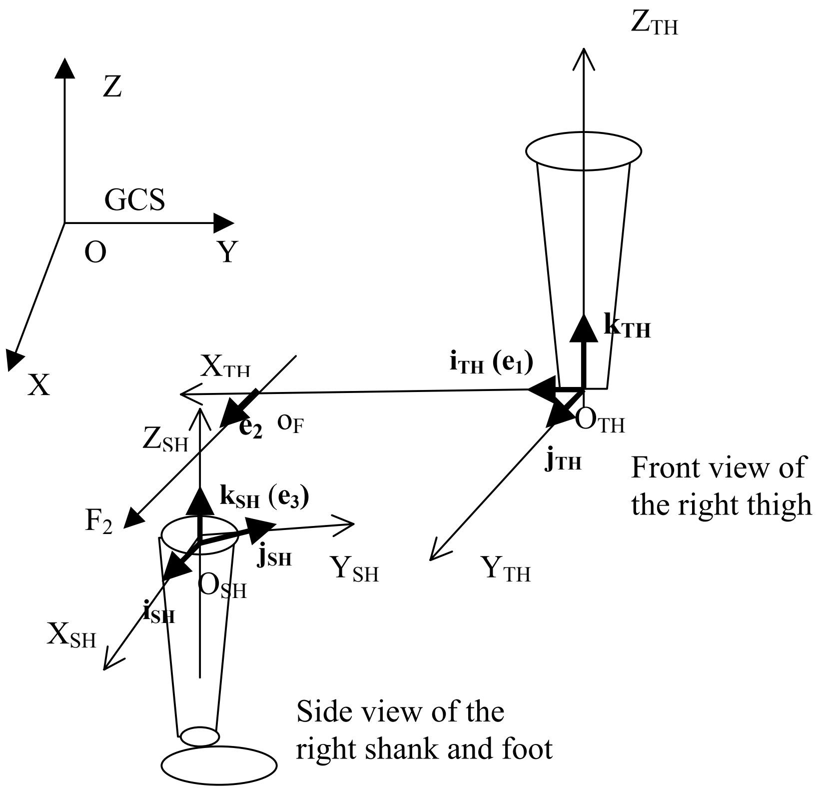


Figure 4.3. Coordinate systems. The GCS is the global coordinate system (X, Y, Z). The Anatomical segmental coordinate systems (ASCS) of the right thigh (X_{TH}, Y_{TH}, Z_{TH}) and shank (X_{SH}, Y_{SH}, Z_{SH}) are shown along with their unit vectors ($<i_{TH}, j_{TH}, k_{TH}>$ and $< i_{TH}, j_{TH}, k_{TH}>$, respectively). The joint coordinate systems (JCS) of the right knee is represented by the unit vectors $<e_1, e_2, e_3>$. Origins of the GCS, ASCSs, and JCS of the thigh and shank are shown (O, O_{TH}, O_{SH} and O_F,), respectively.

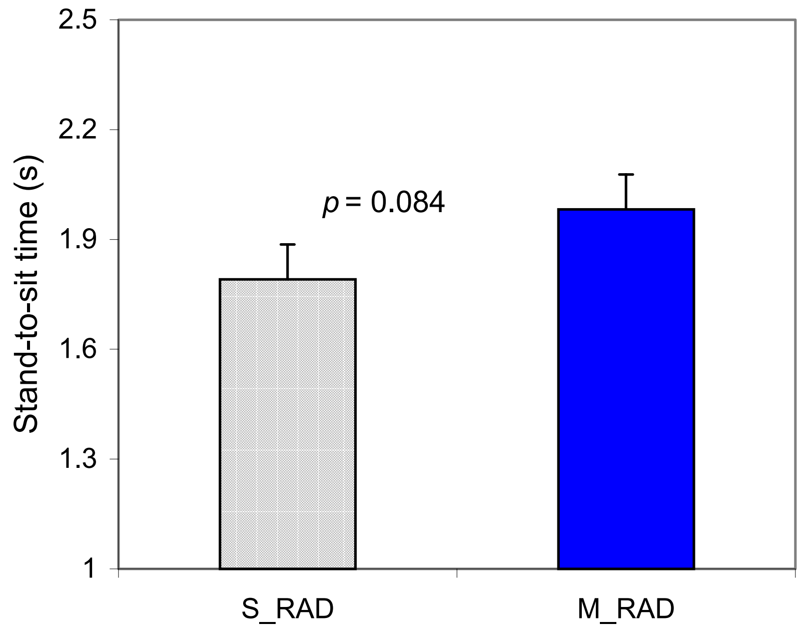


Figure 4.4. Total stand-to-sit time of the S-RAD and M-RAD groups

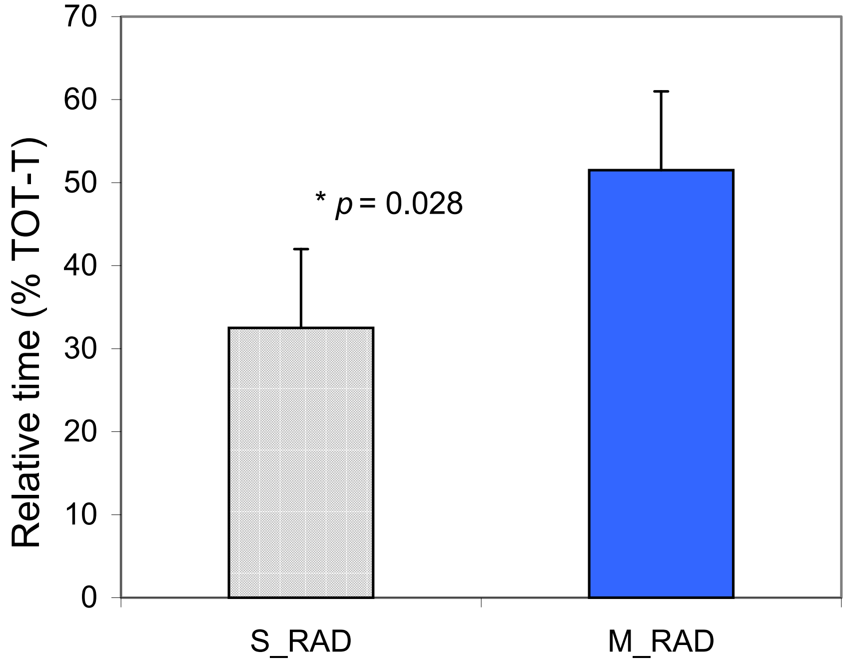


Figure 4.5. Relative time to the ABD peak.

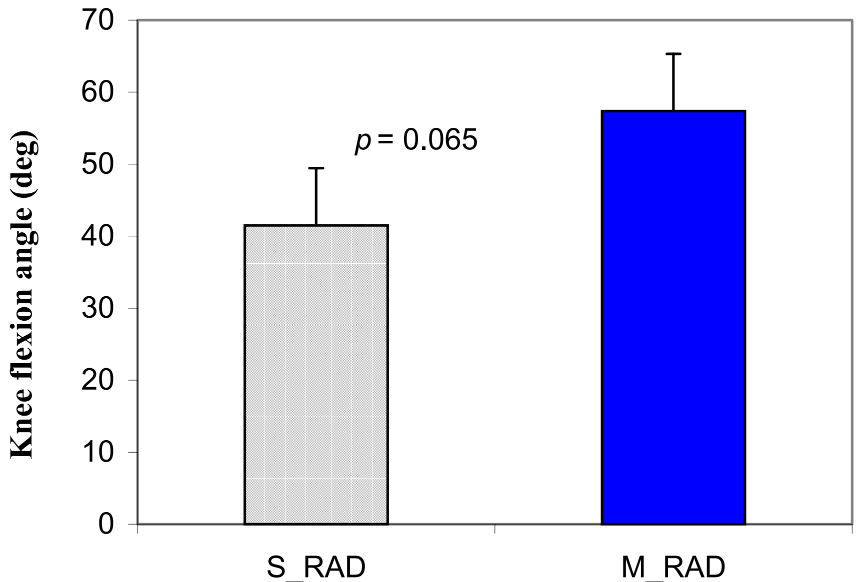


Figure 4.6. Knee flexion angles where the local ABD peak of the TKA limb occurred.

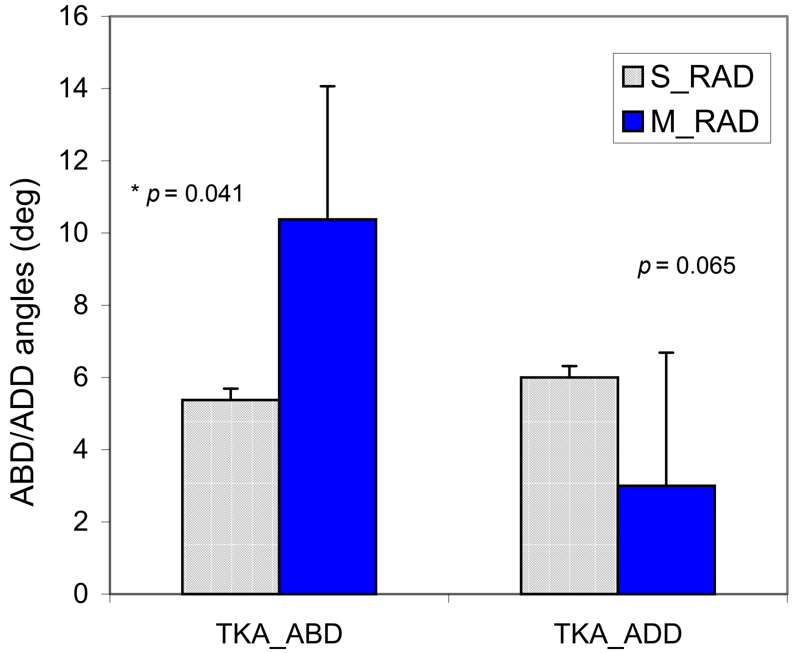
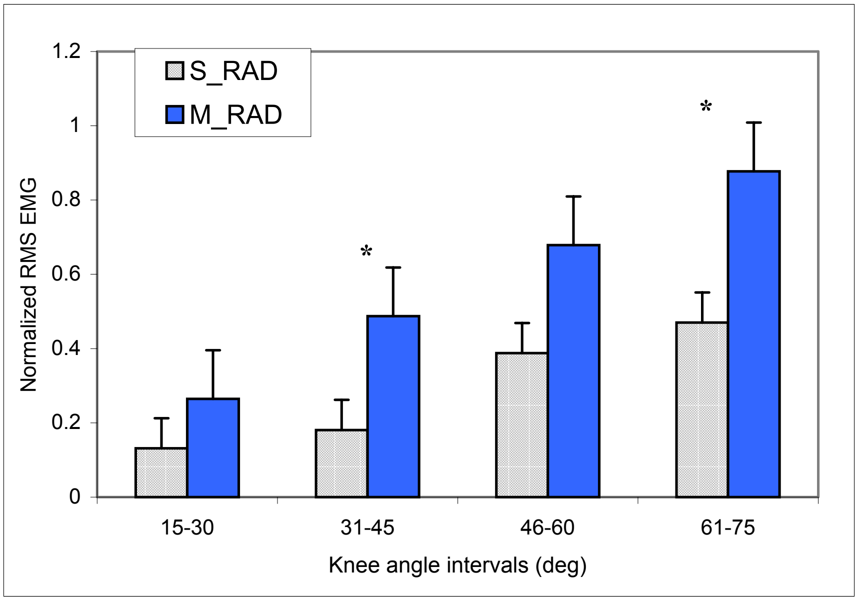


Figure 4.7. ABD and ADD displacement of S-RAD and M-RAD TKA limbs.

VM



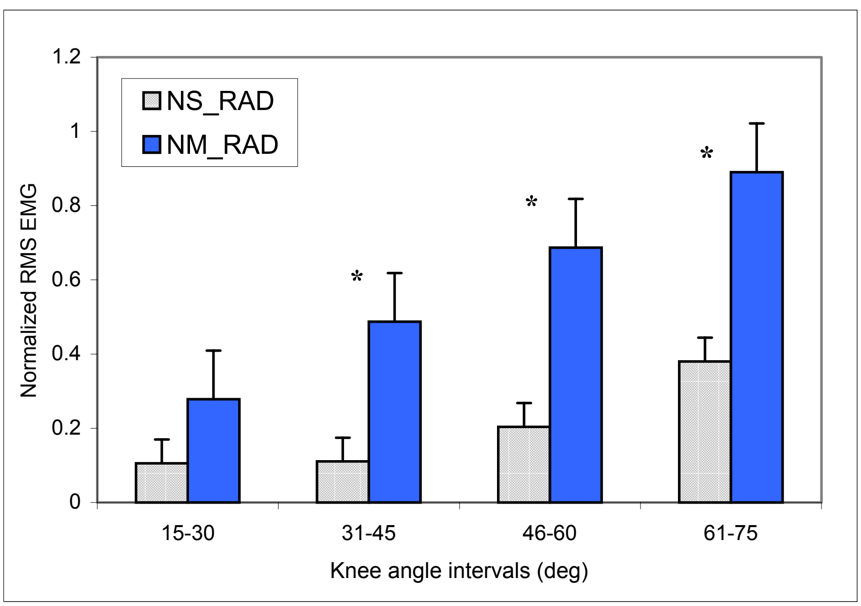
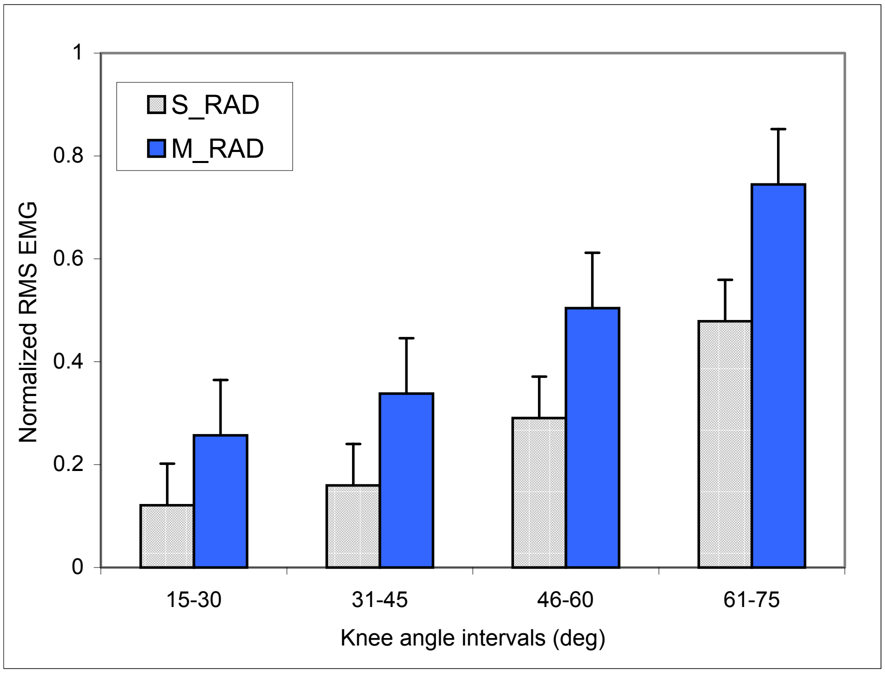


Figure 4.8. RMS EMG for 4 angle intervals from 15 degrees to 75 degrees of knee flexion during knee flexion phase of stand-to-sit movement. VM is shown above for TKA (top) and N-TKA (bottom) limbs. For comparisons between TKA groups: * indicates $p < 0.05$, ** indicates $p < 0.01$.

VL



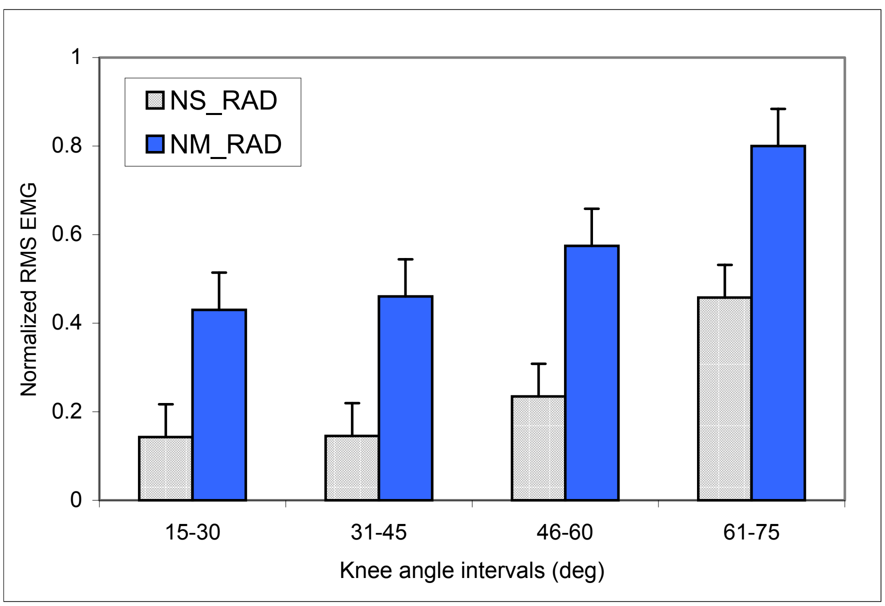
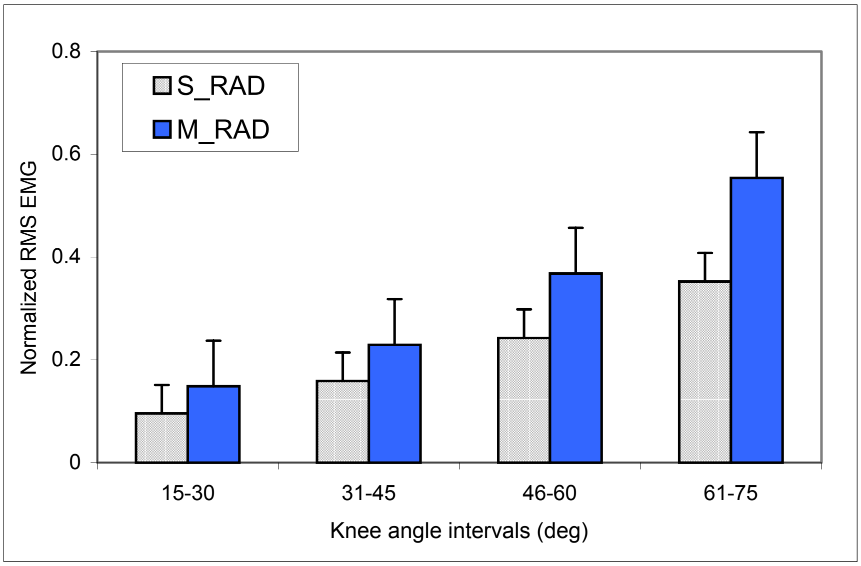


Figure 4.9. RMS EMG for 4 angle intervals from 15 degrees to 75 degrees of knee flexion during knee flexion phase of stand-to-sit movement. VL is shown above for TKA (top) and N-TKA (bottom) limbs. For comparisons between TKA groups: * indicates $p < 0.05$, ** indicates $p < 0.01$.

RF



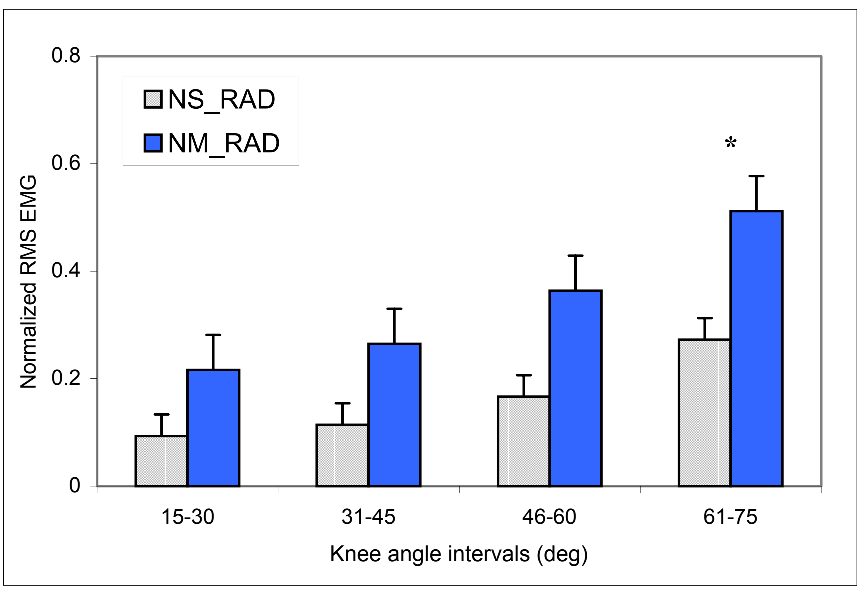
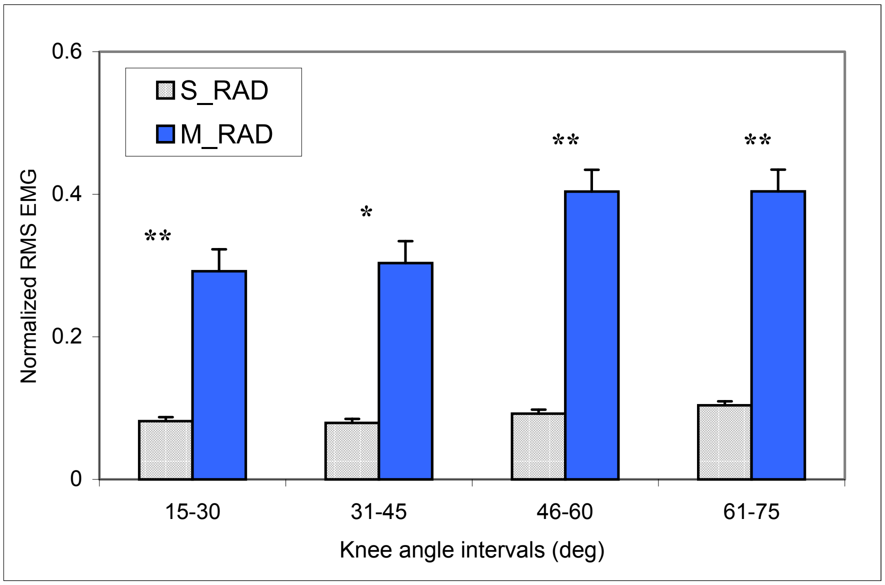


Figure 4.10. RMS EMG for 4 angle intervals from 15 degrees to 75 degrees of knee flexion during knee flexion phase of stand-to-sit movement. RF is shown above for TKA (top) and N-TKA (bottom) limbs. For comparisons between TKA groups: * indicates $p < 0.05$, ** indicates $p < 0.01$.

BF



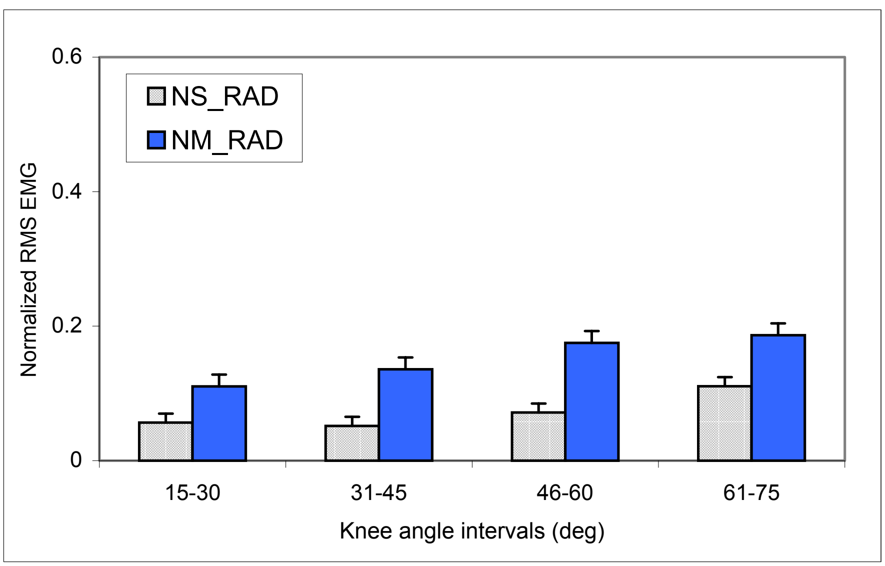
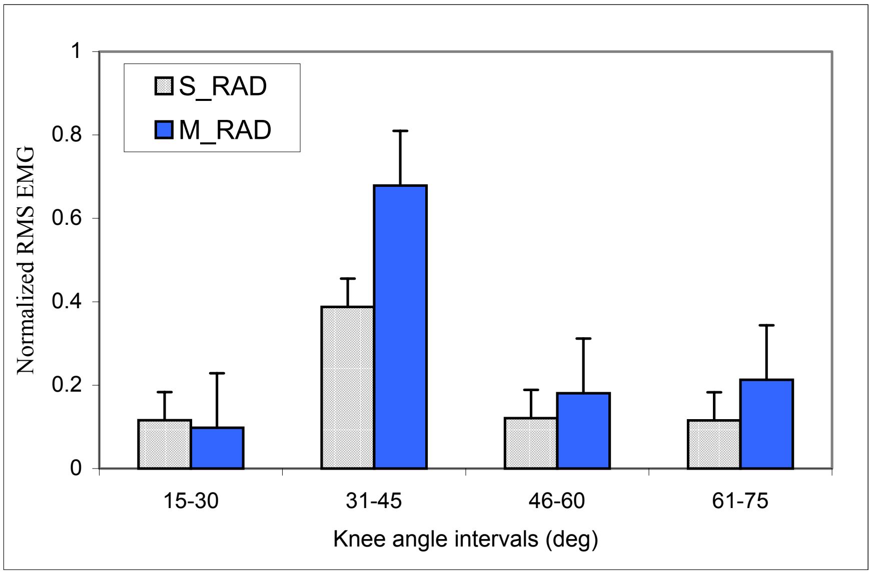


Figure 4.11. RMS EMG for 4 angle intervals from 15 degrees to 75 degrees of knee flexion during knee flexion phase of stand-to-sit movement. BF is shown above for TKA (top) and N-TKA (bottom) limbs. For comparisons between TKA groups: * indicates $p < 0.05$, ** indicates $p < 0.01$.

ST



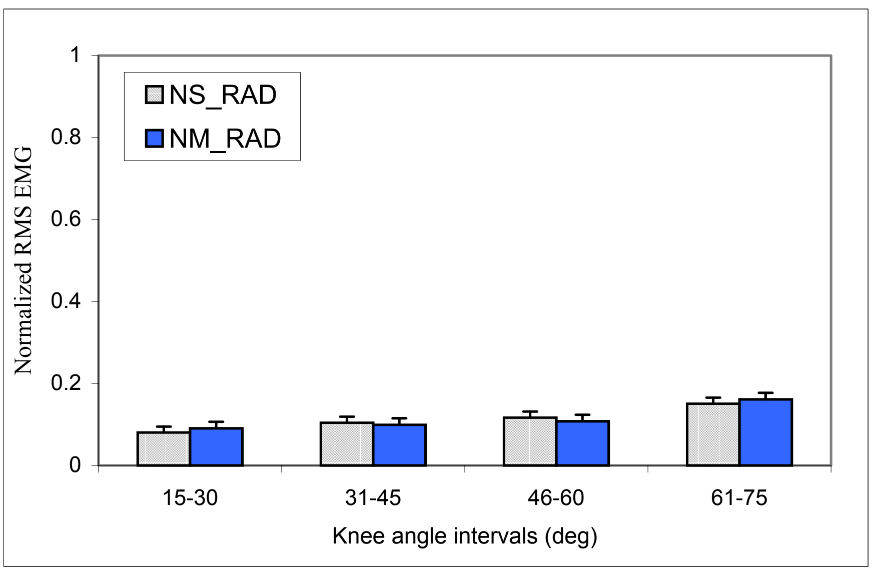


Figure 4.12. RMS EMG for 4 angle intervals from 15 degrees to 75 degrees of knee flexion during knee flexion phase of stand-to-sit movement. ST is shown above for TKA (top) and N-TKA (bottom) limbs. For comparisons between TKA groups: * indicates $p < 0.05$, ** indicates $p < 0.01$.

CHAPTER 5

SUMMARY AND CONCLUSIONS

The purpose of these two studies was to investigate the effect of a single KNEE FLEX/EXT axis versus two axes on knee joint kinematics and muscle activity reflecting functional performance during sit-to-stand and stand-to-sit movements. As standing up requires greater knee extension torque than walking and stair climbing (Berger et al., 1988) and sitting down necessitates adequate knee extensor eccentric force and knee stability in order to avoid falling, a better understanding of the functional impact of TKA design differences on the ability to perform daily activities that are very demanding of KNEE FLEX/EXT muscles was possible.

For this retrospective study, after prescreening potential 18^{+} mo. post-operative unilateral TKA individuals, participants were selected for the single-radius (n = 8) and multi-radius (n = 8) TKA design groups. While the participants performed four trials each of the sit-to-stand and the stand-to-sit movements, motion was captured via high-speed 3D videography; and electrical activity of selected quadriceps and hamstring muscles was acquired. One-way ANOVAs were conducted to determine the kinematic and EMG differences between the two TKA groups (α = 0.05).

The results of both studies demonstrated partial support for the two major premises of the study. Compared to an M-RAD TKA design, for the S-RAD design, a) the greater extensor mechanism would either reduce the relative amount of muscle activation and/or minimize the need to exhibit compensatory movements; and b) having only one KNEE FLEX/EXT axis compared to two axes would increase medio-lateral stability.

For the sit-to-stand study, we found that the M-RAD group demonstrated significantly different kinematics and knee muscular activation from the S-RAD group. First, compared to the S-RAD group, the M-RAD group showed significantly longer sit-to-stand time, more trunk flexion, and a tendency of greater trunk flexion velocity ($p = 0.058$). In addition, the M-RAD group, compared to the S-RAD group, displayed greater TKA limb quadriceps activation. These findings were evidences of adaptations made by the M-RAD participants to compensate for a relatively weaker TKA limb, potentially due to the shorter knee extension muscle moment arm and/or less muscle force generation.

Second, in regards to medio-lateral knee stability, the M-RAD TKA limb tended to exhibit an ABD movement during the trunk flexion phase and greater ADD displacement during the knee extension phase. Greater hamstrings co-activation EMG was also displayed by the M-RAD TKA limb, perhaps as a mean of stabilizing the unstable TKA knee. Hence, these results suggest that the midflexion instability phenomenon experienced by some M-RAD TKA individuals may be due to the abrupt shift in radius length from the longer to the shorter radius when rising from a chair.

For the stand-to-sit study, we also found support for functional advantages of a single KN_FLEX/EXT axis versus multiple axes. The M-RAD TKA group demonstrated greater TKA limb quadriceps eccentric actions than the S-RAD group. One explanation is that with a shorter quadriceps moment arm for an M-RAD TKA than an equivalent S-RAD TKA, in order to produce the desired level of knee extension muscle torque needed to counteract the proximal joint reaction moment, the M-RAD group needed to increase the quadriceps eccentric activity.

Evidences of decreased medio-lateral stability and efforts to stabilize the TKA knee were demonstrated by the M-RAD group also during the stand-to-sit. For the TKA limb, The M-RAD group exhibited a greater ABD displacement than the S-RAD group. In addition, the ABD peak displayed by the TKA limb occurred significantly later for the M-RAD group compared to the S-RAD group. These suggested that the M-RAD TKA limb might not be able to effectively restrict its frontal plane motion. Furthermore, the M-RAD TKA limb displayed greater hamstrings co-activation EMG than the S-RAD TKA limb, possibly in anticipation of and during the shift to one KN_FLEX/EXT axis from the other.

In conclusion, the design differences regarding KN_FLEX/EXT axes between the M-RAD and S-RAD TKAs could lead to significant differences related to functional performance, as reflected by lower extremity kinematics and electrical activation of various knee muscles that produce knee extension/flexion moments during these daily movements of standing up and lowering the body to sit down. Compared to the M-RAD TKA design, the S-RAD TKA design could enhance the knee extension mechanism, consequently requiring relatively less quadriceps activation and/or no compensatory adaptations. The S-RAD TKA design may be enhancing facilitate medio-lateral knee stability by maintaining adequate and appropriate tension of the collateral ligaments during knee FLEX/EXT movements when raising and lowering the body.

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APPENDICES

Appendix A

Knee Society Clinical Rating System Form

Knee Society Clinical Rating System

Participant ID # ______________

Patient Category:

A. Unilateral or bilateral (opposite knee successfully replaced)
B. Unilateral, other knee symptomatic
C. Multiple sclerosis or medical infirmity

Clinical	Points
Pain	
None	50
Mild or occasional	45
Stairs only	40
Walking and stairs	30
Moderate	
Occasional	20
Continual	10
Severe	0
Range of Motion	
(5° = 1 point)	25 (max)
Stability (maximum movement)	
Anteroposterior	
<5 mm	10
5-10 mm	5
10 mm	0
Mediolateral	
<5°	15
6°-9°	10
10°-14°	5
15°	0
Subtotal:	______
Deductions	
Flexion contracture	
5°-10°	2
10°-15°	5
16°-20°	10
>20°	15
Extension lag	
<10°	5
10°-20°	10
>20°	15
Alignment	
5°-10°	0
0°-4°	3 points each degree
11°-15°	3 points each degree
Other	20
Total deductions:	______
Clinical score:	______

Functional	Points
Walking	
Unlimited	50
>10 blocks	40
5-10 blocks	30
<5 blocks	20
Housebound	10
Unable	0
Stairs	
Normal up and down	50
Normal up; down with rail	40
Up and down with rail	30
Up with rail; unable down	15
Unable	0
Subtotal:	______
Deductions	
Cane	5
Two canes	10
Crutches or walker	20
Total deductions:	______
Functional score:	______

Appendix B

Participant Consent Form

Consent Form

I agree to participate in the research titled, **A Comparison of a Single-Radius versus Multi-Radius Total Knee Replacement System on Functional Outcomes** which is being conducted by Dr. Michael S. Ferrara (542-4801) and Dr. Kathy Simpson (542-4385) of the Dept. of Exercise Science. I understand that this participation is entirely voluntary; I can withdraw my consent at any time without penalty and have the results of the participation, to the extent that it can be identified as mine, returned to me, removed from the research records or destroyed.

The following points have been explained to me:

1. The research is being conducted to study the differences in functional outcomes between two different knee prosthetic devises used for knee replacement systems.

2. The procedures are as follows: I will receive a detailed explanation of the study, the benefits and risk of participation and sign the informed consent. I understand that the testing will consist of the following: range of motion assessment of both knees, balance and functional testing using the NeuroCom, sit to stand, and strength testing using the Kin-Com. I will allow a surface EMG unit which measures muscle activity to be attached to the front part of my leg for the testing of strength and balance. Also, my sit to stand will be video taped from the waist down to assist in calculating peak force and joint angles during this movement. I will be provided a warm-up on a stationary bicycle and stretching program prior to beginning the testing to reduce the likelihood of injury. I understand that the total time for the testing should be about 90-120 minutes.

3. The benefit that I may expect from this research is to expand the knowledge and understanding of different knee replacement systems. At the conclusion of the study, I will receive a functional analysis about my performance on the various tests that I participated in.

4. You have minimal risk of injury from your participation in this project. Although, it is highly unlikely, the only potential injury that may occur would be from a fall during the balance testing or you may experience some muscle soreness the next day from the strength testing. However, trained spotters will be used to assist you in maintaining balance should you fall. Prior to testing, we will also instruct you on a proper warm-up to reduce the possibility of a muscle injury. In the event of injury resulting from participating in this project, immediate first aid is provided. If additional care is needed, I will be transported to a local hospital of my choice and I will be responsible for any expense that may be incurred.

5. If at any time during the testing, your experience pain, let the investigators know IMMEDIATELY so that an informed decision may be made about continuance of the study.
6. The results of this participation will be confidential and will not be released in any individually identifiably form without my prior written consent, unless otherwise required by law.

7. The investigators will answer any further questions about the research, now or during the course of the project and can be reached at 706-542-4801 for Dr. Ferrara and 706-542-4835 for Dr. Simpson.

_______________________________ _____________
Signature of Researcher Date

Please sign both copies of this form. Keep one copy and return the other to the investigator.

Research at the University of Georgia that involves human participation is overseen by the Institutional Review Board. Questions or problems regarding your rights as a participant should be addressed to Julia D. Alexander, MA, Institutional Review Board, Office of the Vice President for Research, University of Georgia, 606A Boyd Graduate Studies Research Center, Athens, Georgia, 3060207411; Telephone (706)542-6514,e-mail JDA@ovpr.uga.edu.

Appendix C

Pretest Questionnaire

UGA Total Knee Replacement Participant Health and Activity Questionnaire

Name ______________________________ Date ___/___/____

For the following questions, we are interested in your health primarily since the last time you visited Dr. Mahoney's clinic.

Have you previously had or presently have any of the following medical conditions If yes, please indicate the date of first symptoms or diagnosis by month/year (for example 1/98)

Date	Previously	Presently	
____	______	_____	Pain in heart or chest
____	______	_____	Heart attack
____	______	_____	Heart Murmur
____	______	_____	Extra or skipped heart beats
____	______	_____	Abnormal EKG
____	______	_____	Any heart problems: specify ____________________
____	______	_____	Phlebitis
____	______	_____	Dizziness or fainting spells
____	______	_____	Stroke
____	______	_____	Badly swollen ankles
____	______	_____	Hypertension
____	______	_____	Scarlet Fever
____	______	_____	Gout
____	______	_____	Diabetes
____	______	_____	Epilepsy
____	______	_____	Asthma
____	______	_____	Other lung diseases: specify ____________________
____	______	_____	Nervous or emotional problems
____	______	_____	Injuries to back, arms, legs or joints
____	______	_____	Back pain
____	______	_____	Swollen, stiff or painful joints
____	______	_____	Arthritis of arms or legs
____	______	_____	Allergies to adhesive tape or to gels used for EKG or ultrasound

Explanation or Comments: ____

____

____

Date of last complete medical exam: _________ Were the results normal? Yes/ No
If NO, explain ____

____

____

Do you know of any medical problems that might make it unwise for you to participate in any of the following activities:

a. Test the strength of your upper leg muscles using maximal effort? Yes/No
b. Standing on a single leg for approximately 10 seconds repetitively? Yes/No
c. Rise from a chair to a standing position without the use of your arms or hands to help push you up? Yes/No

If Yes, explain ____

____

____

Have you started taking medications or changed the dosages of any medications that have the following side effects:

a. Balance problems? Yes/No
b. Produces nausea during physical activity? Yes/No
c. Dizziness? Yes/No
d. Vision? Yes/No
e. Hand-eye coordination? Yes/No

Physical Activity

Mark the activities in which you currently participate:

Golf	_____	Bowling	_____
Dance	_____	Tai Chi	_____
Cycling	_____	Water Exercises	_____
Walking	_____	Weight Lifting	_____
Running	_____	Physical Therapy	_____
Swimming	_____	Tennis	_____
Aerobics	_____	Housework	_____
Gardening	_____	Yardwork	_____

Appendix D

Posttest Questionnaire

Participant # _________
Date _____________
Day 3

Perception Questionnaire for TKR study

(Please answer the following questions based on today's testing with a Yes or No answer.)

Previous testing

1. Were you sore from the previous testing? Y/N
If yes, what was sore and how long did it last? ____________________

____

2. Did you have any reaction to the tape or electrodes that were placed on your legs during the previous testing session? Y/N
If yes, explain (for prevention purposes)____________________

____

Any questions on today's procedures?

Is there anything that can be done to make you more comfortable than your previous testing session?

Warm-up

1. Did you feel the warm-up time was adequate to effectively perform the tasks? _____ not enough time _____ just right _____ too long
2. Did you experience any pain during the warm up period? Y / N
Explain if pain was experienced ____________________

____

KinCom

1. Did you feel at ease in the room? Y /N
If no, how can we make you more comfortable? ____________________

____

2. Did you feel comfortable in the apparatus for testing leg strength? Y/ N
If no, how can we make you more at ease?____________________

____

3. Did you feel straps were too tight on the thigh? Y/N on the ankle? Y/N
4. Did you understand the tasks to be completed during the leg strength portion of the test? Y / N

Participant # ________
Date ____________
Day 3

If no, what part did you not understand a) when to push or pull b) when arm of apparatus will move c) direction arm of apparatus will move d) other ______________________________

5. Did you feel more comfortable during the leg strength testing today than previous testing days? Y/N Explain the differences felt between the days. ______________________________

____

Right Leg

1. In each of the pushing tasks, did you push as hard as you could? If No, explain why. ______________________________

____

2. In each of the pulling tasks, did you pull as hard as you could? If No, explain why. ______________________________

____

Left Leg

1. In each of the pushing tasks, did you push as hard as you could? If No, explain why. ______________________________

____

2. In each of the pulling tasks, did you pull as hard as you could? If No, explain why. ______________________________

____

EMG of KinCom

1. Did you feel at ease with the placement of the electrodes? Y/N
2. Did you feel any discomfort from the electrodes? Y/N
3. Did you feel the wires from the electrodes hampered your movement for any of the tests? Y/N

General Comments: ______________________________

____

____

____

Appendix E

Calculation of the Joint Coordinate System

Calculation of transform matrix [T_{O1}] between global coordinate system and dynamic coordinate system of the thigh

Step 1: Create a Dynamic coordinate system (O_1- $X_1Y_1Z_1$) (DCS) on the thigh based on point A, B, and D.

The coordinates of point A, B, C are known in the global coordinate system (GCS)(O – XYZ).

Let the origin O_1 be at the point B. Let $\mathbf{I_1}$, $\mathbf{J_1}$, and $\mathbf{K_1}$ represent the unit vectors of O_1- $X_1Y_1Z_1$. Let **I**, **J**, and **K** represent the unit vectors of GCS O-XYZ.

Figure E.1. shows the GCS, DCS of thigh.

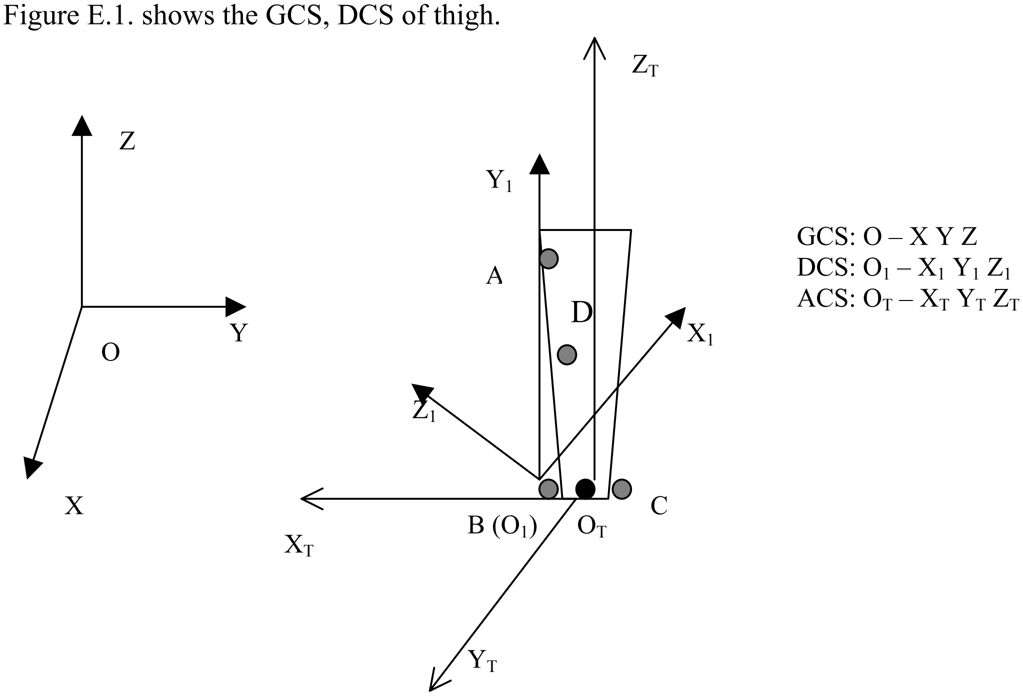

Figure E.1. GCS, DCS, and ACS of thigh

$\boldsymbol{J_1 = O_1A_{(G)}/|O_1A|_{(G)}}$

$\boldsymbol{K_1 = (O_1D_{(G)} \times O_1A_{(G)})/|\, O_1D_{(G)} \times O_1A_{(G)}|}$

$\boldsymbol{I_1 = J_1 \times K_1}$

Step 2: Calculate the rotation matrix $[R_{O1}]$.

Let $[R_{O1}]$ represent the rotation matrix between the dynamic coordinate system O_1- $X_1Y_1Z_1$ and GCS O-XYZ.

Then,

$$[R_{O1}] = \begin{pmatrix} \mathbf{I \bullet I_1} & \mathbf{I \bullet J_1} & \mathbf{I \bullet K_1} \\ \mathbf{J \bullet I_1} & \mathbf{J \bullet J_1} & \mathbf{J \bullet K_1} \\ \mathbf{K \bullet I_1} & \mathbf{K \bullet J_1} & \mathbf{K \bullet K_1} \end{pmatrix}$$

$$[T_{O1}] = \left(\begin{array}{c:c} 1 & 0\ 0\ 0 \\ \hdashline \{\mathbf{OO_1}\}_{(G)} & [R_{O1}] \end{array}\right)$$

$$[T_{O1}]^{-1} = \left(\begin{array}{c:c} 1 & 0\ 0\ 0 \\ \hdashline -[R_{O1}]^{-1}\{\mathbf{OO_1}\}_{(G)} & [R_{O1}]^{-1} \end{array}\right)$$

Step 3: Calculation of Thigh anatomic coordinate system (ACS)

Let O_T be the origin of the thigh anatomical coordinate system (ACS) $O_T - X_TY_TZ_T$.

Let $\mathbf{I_T}$, $\mathbf{J_T}$, and $\mathbf{K_T}$ represent the unit vectors of O_T- $X_TY_TZ_T$(Figure 3).

$\boldsymbol{I_T = O_1B_{(G)}/|O_1B|_{(G)}}$

$\boldsymbol{J_T = (O_TA_{(G)} \times O_TB_{(G)})/|O_TA_{(G)} \times O_TB_{(G)}|}$

$\boldsymbol{K_T = I_T \times J_T}$

Calculation of Shank ACS O_S - $X_SY_SZ_S$

Figure E.2 shows the GCS, ACS of the shank and thigh.

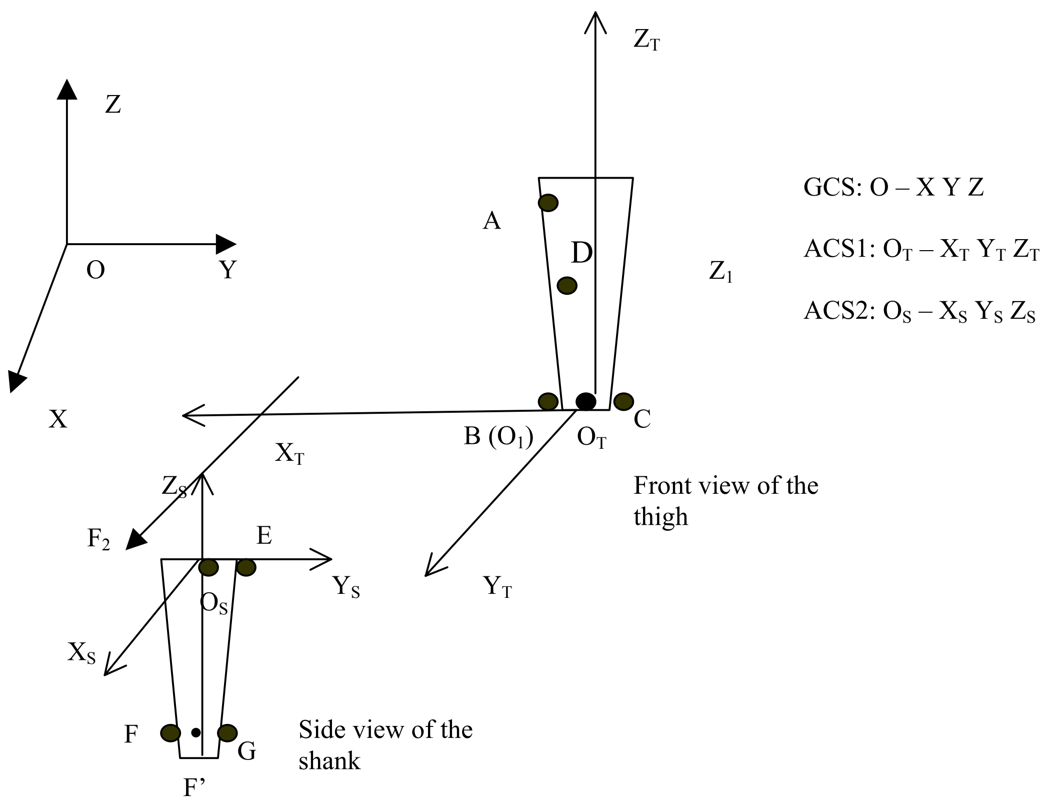

Figure E.2. ACS of thigh and shank

Step 1. Obtain the global coordinate of the origin O_S.

Let F' be the midpoint of line FG. Then, the global coordinates of F' will be,

$$F'_X = F_X + (G_X - F_X)/2$$

$$F'_Y = F_Y + (G_Y - F_Y)/2$$

$$F'_Z = F_Z + (G_Z - F_Z)/2$$

$$(O_SE_{(G)}/|O_SE|_{(G)}) \bullet (FG_{(G)}/|FG|_{(G)}) = 1 \qquad (1)$$

$$O_SE_{(G)} \bullet F'O_{S(G)} = 0 \qquad (2)$$

$$F'O_{S(G)} \bullet FG_{(G)} = 0 \qquad (3)$$

From equation (1), (2), and (3), the global coordinates of O_S (O_{SX},O_{SX},O_{SX}) can be obtained.

Step 2: Create the shank ACS ($O_S - X_S\ Y_S\ Z_S$).

Let $\mathbf{I_S}$, $\mathbf{J_S}$, and $\mathbf{K_S}$ represent the unit vectors of shank ACS.

Then,

$$\boldsymbol{I_S = J_S \times K_S}$$

$$\boldsymbol{J_S = O_SE_{(G)}/|O_SE|_{(G)}}$$

$$\boldsymbol{K_S = F'O_{S(G)}/|F'O_S|_{(G)}}$$

Calculation of the transformation matrix [T_{TF}] between JCS and ACS of the thigh

Let O_F - $X_FY_FZ_F$ represent the JCS.

Then,

$$\boldsymbol{O_TO_{S(LF)} = S_1e_1 + S_2e_2 + S_3e_3} \qquad \textbf{(1)}$$

$$\boldsymbol{O_TO_{S(LT)} = X_TI_T + Y_TJ_T + Z_TK_T} \qquad \textbf{(2)}$$

$$[R_{TF}] = \begin{bmatrix} \mathbf{I_T \bullet e_1} & \mathbf{I_T \bullet e_2} & \mathbf{I_T \bullet e_3} \\ \mathbf{J_T \bullet e_1} & \mathbf{J_T \bullet e_2} & \mathbf{J_T \bullet e_3} \\ \mathbf{K_T \bullet e_1} & \mathbf{K_T \bullet e_2} & \mathbf{K_T \bullet e_3} \end{bmatrix} \qquad (3)$$

$$[T_{TF}] = \left[\begin{array}{c:c} 1 & 0\ 0\ 0 \\ \hdashline \{\mathbf{O_TO_F}\}_{(LT)} & [R_{TF}] \end{array}\right] \qquad (4)$$

$$\{\mathbf{O_TO_F}\}_{(LT)} = \begin{Bmatrix} S_1 \\ 0 \\ 0 \end{Bmatrix} \qquad (5)$$

Appendix F

Samples of kinematic graphs of the sit-to-stand

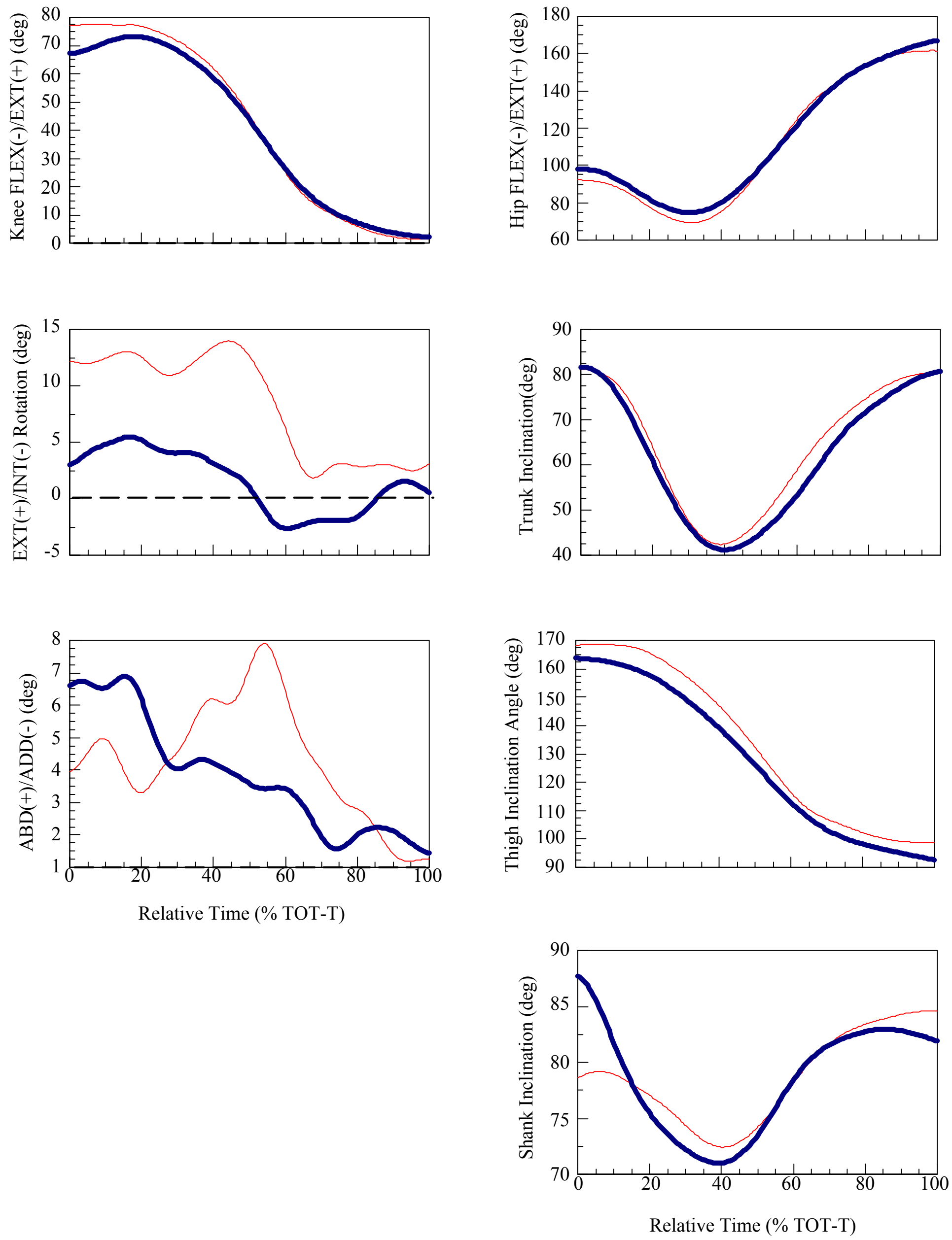

Figure F.1. Relative Knee Angles, Hip Angle, Trunk, Thigh, and Shank inclination Angles As a Function of Time. The TKA (thin line) and N-TKA (thick line) limbs of A Representative Multi-Radius Participant.

Note. The unit of the horizontal axis is the percentage of sit-to-stand time (% TOT-T)

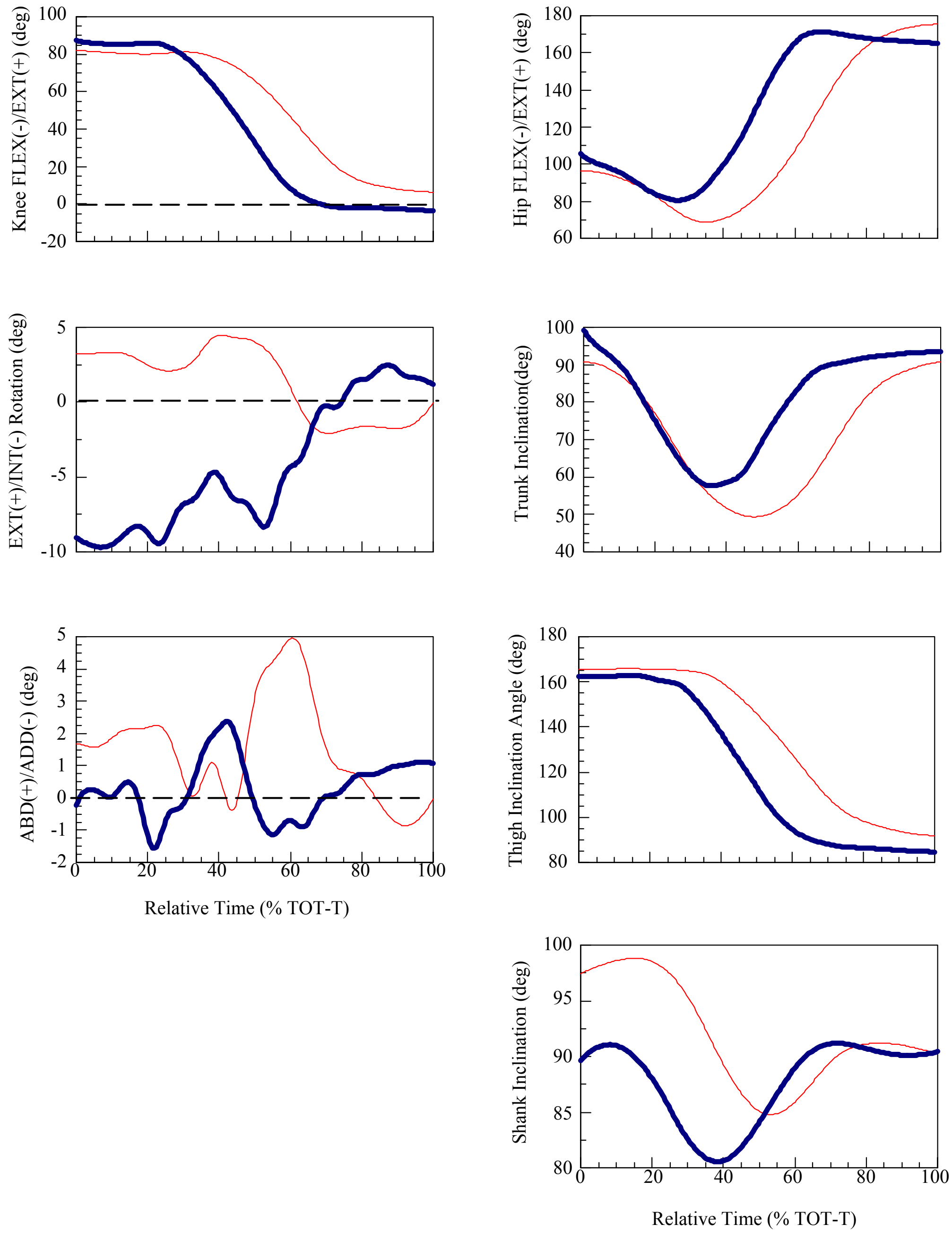

Figure F.2. Relative Knee Angles, Hip Angle, Trunk, Thigh, and Shank inclination Angles As a Function of Time. The TKA (thin line) and N-TKA (thick line) limbs of A Representative Single-Radius Participant.

Note. The unit of the horizontal axis is the percentage of sit-to-stand time (% TOT-T)

Samples of kinematic graphs of the stand-to-sit

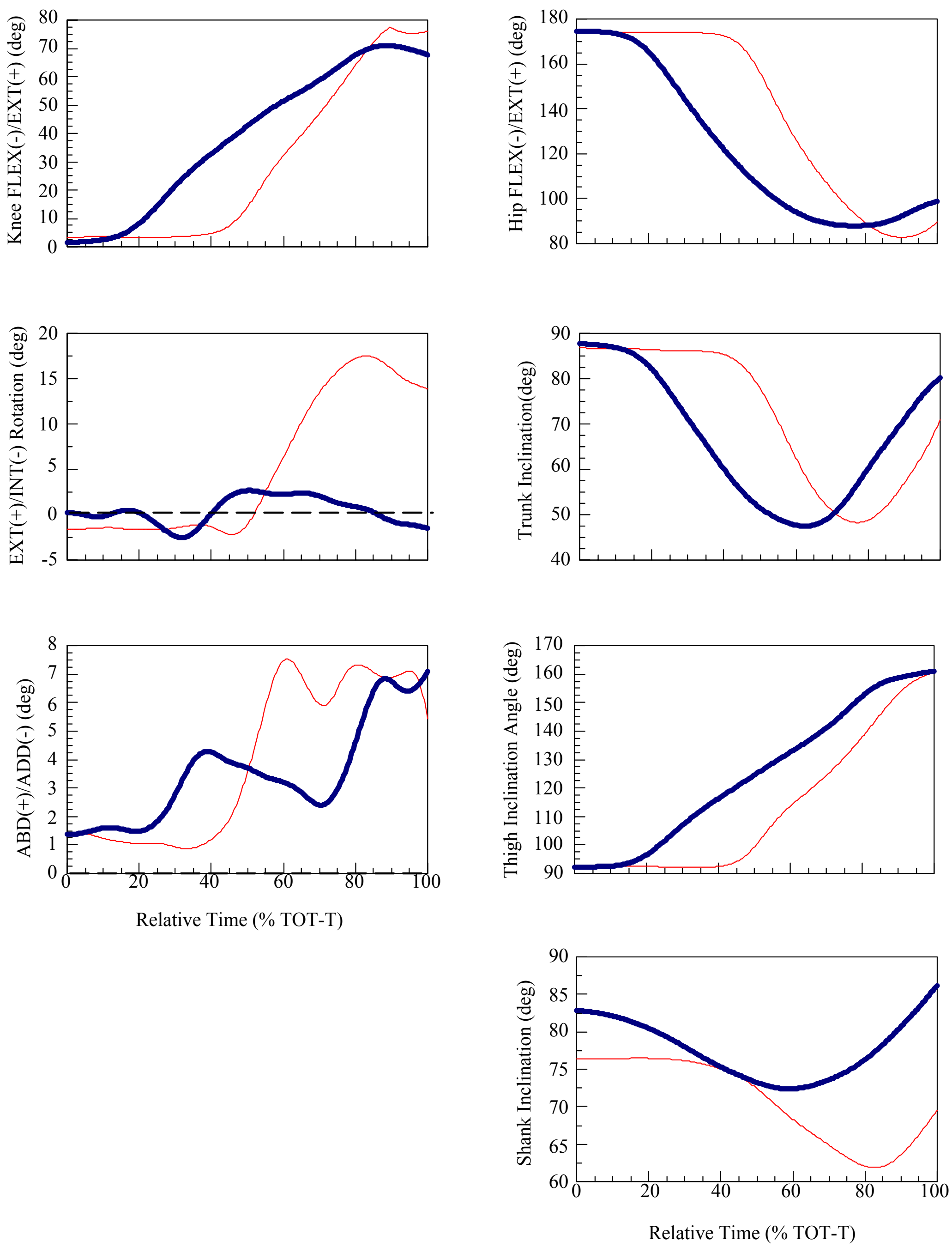

Figure F.3. Relative Knee Angles, Hip Angle, Trunk, Thigh, and Shank inclination Angles As a Function of Time. The TKA (thin line) and N-TKA (thick line) limbs of A Representative Multi-Radius Participant.

Note. The unit of the horizontal axis is the percentage of stand-to-sit time (% TOT-T)

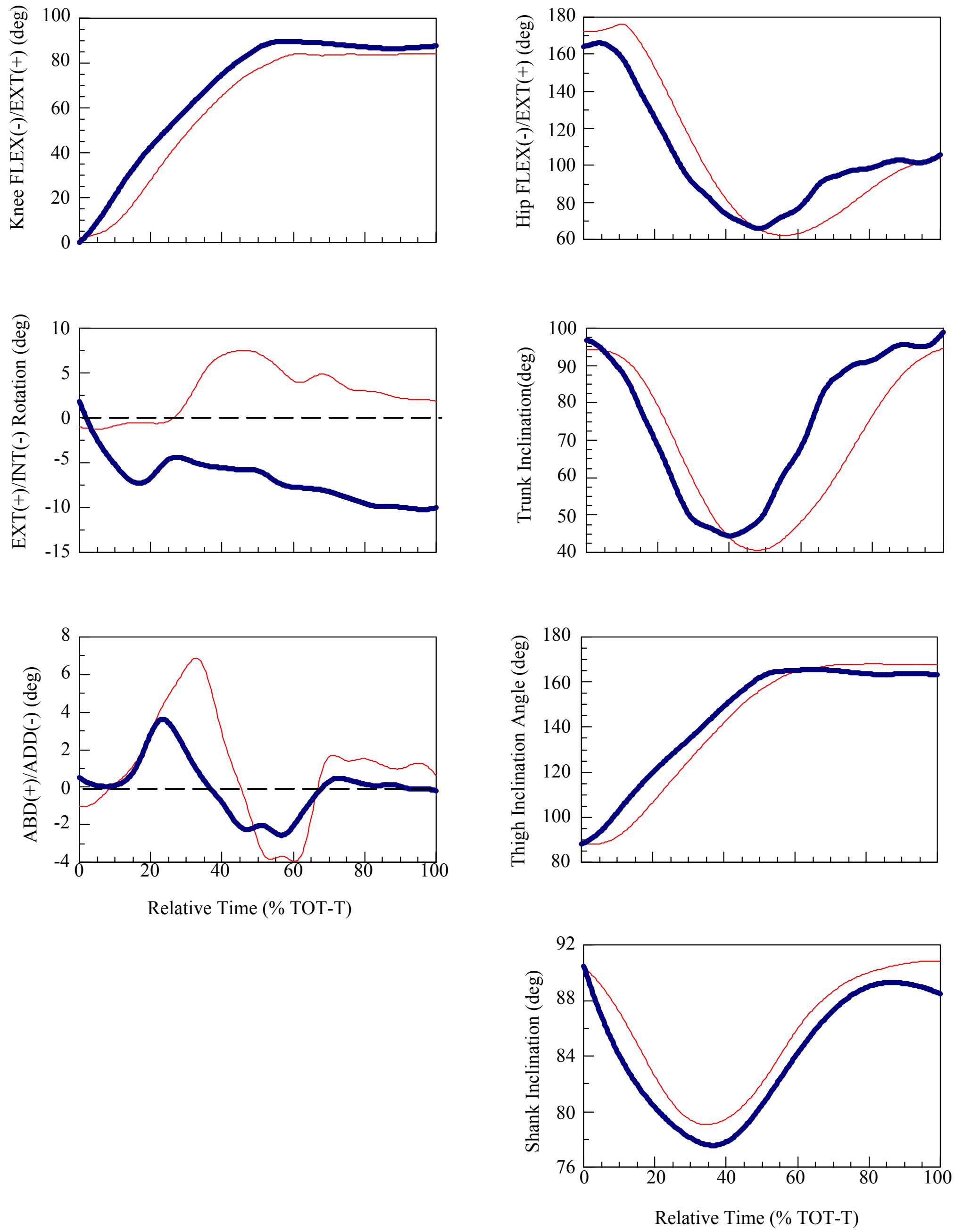

Figure F.4. Relative Knee Angles, Hip Angle, Trunk, Thigh, and Shank inclination Angles As a Function of Time. The TKA (thin line) and N-TKA (thick line) limbs of A Representative Single-Radius Participant.

Note. The unit of the horizontal axis is the percentage of sit-to-stand time (% TOT-T)