Journal of Life Science 2006 Vol. 16. No. 5. 773~779 ©JLS

A Biomechanical Comparative Analysis between Single-Radius and Multi-Radius Total Knee Arthroplasty for Sit-to-Stand Movement

Young Wan Jin*

Department of Leisure & Sport Science, Dongeui University, Busan 614-714, Korea

Received June 3, 2006 / Accepted July 21, 2006

Eight of the individuals had a unilateral S-RAD TKA and Multi-Radius TKA (Scorpio^{TM} PS, Howmedica-Osteonics, Inc.). The instrument were used Peak Motion Measurement System^{TM} ,MYOPAC^{TM}EMG System, KIN-COM III^{TM} System. The Figure 3 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). In Figure 5, 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). The Figure 6 shows that the S-RAD TKA limb tended to have less ADD displacement (p = 0.071) than that of the M-RAD TKA limb. 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). 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).

Key words – Multi-radius, single-radius, TKA, biomechanics

Introduction

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[10]. 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). Two major muscle groups around the knee joint are knee extensors and knee flexors. The quadriceps is the primary knee extenmor 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. 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[8]. 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 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[8]. 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)(Fig. 1). In addition, there are limited antero-posterior and medio-lateral translations. Total knee arthroplasty (TKA) has been used since 1950s[4]. 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 per-

---

*Corresponding author
Tel : +82-51-890-2211, Fax : +82-51-890-2157
E-mail : ywjin@deu.ac.kr

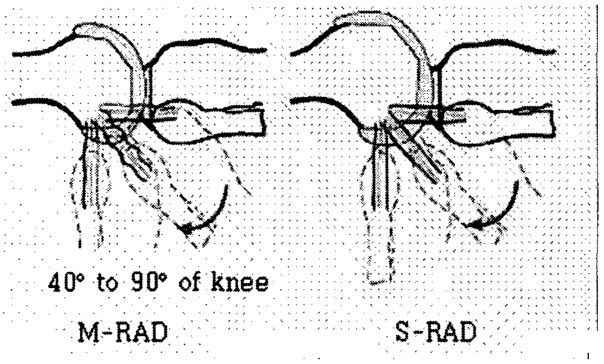

Fig. 1. Surmised collateral ligament lengths of an M-RAD and an S-RAD TKAs during knee flexion.

manent fixation of the joint by surgery) was the recommended treatment of OA and RA. However an arthrodesis could not provide mobility to the knee[6]. 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[3]. The sit-to-stand movement requires greater knee extension torque generated by quadriceps muscles than level walking and climbing stairs[1]. 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[2]. 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. The purpose of this study was to investigate the effect of differences TKA designs on knee kinematic and muscularactivation for the sit-to-stand movement.

Materials and Methods

Participant

Means ± standard deviations for participant (8 peoples) characteristics were age (65±3 yr), weight (87±4 kg), and height (1.76±0.5 m).

Peak motion measurement system

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

EMG system

A 16-channel MYOPAC^{TM}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^{TM}, 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.

KIN-COM III system

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.

Results

The Fig. 2 shows that the average time for the S-RAD

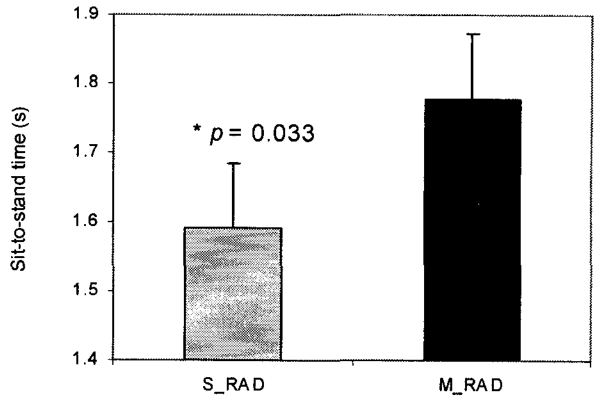

Fig. 2. Total sit-to-stand time of the S-RAD and M-RAD groups.

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 Fig. 3 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 Fig. 4, 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 (42º • s^{-1} for both groups, p = 0.957). The TKA_ABD and TKA_ADD represent the TKA limb ABD and ADD displacement, respectively. The Fig. 5 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

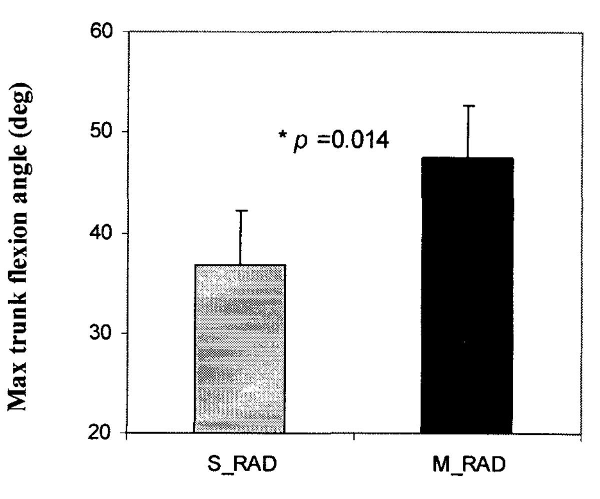

Fig. 3. Minimum trunk flexion angle during phase I of the sit-to-stand.

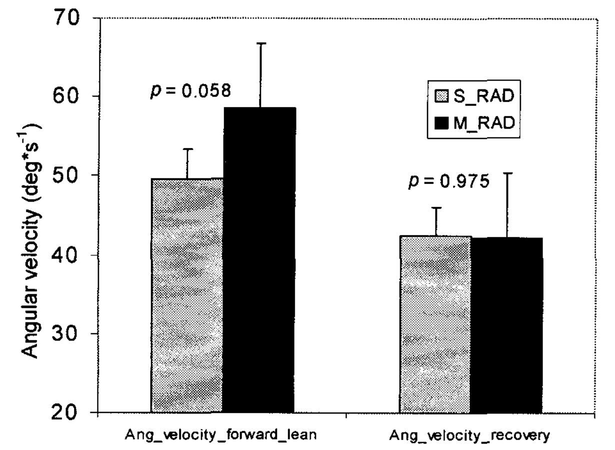

Fig. 4. Average angular velocities of trunk flexion during Phase I and trunk extension during Phase II.

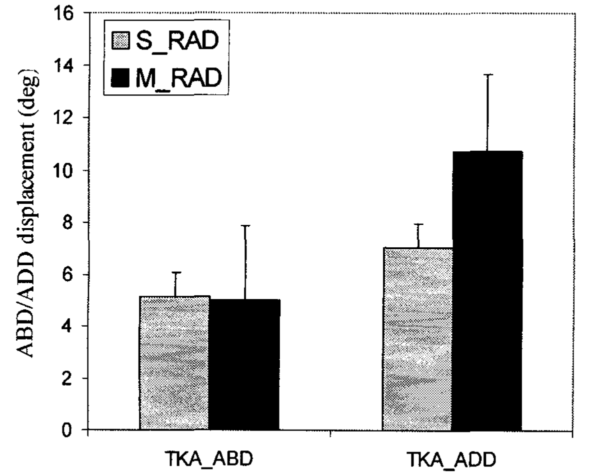

Fig. 5. ABD and ADD displacement of S-RAD and M-RAD TKA limbs.

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 Fig. 6 - 8 showed the quadriceps EMG results for the TKA and N-TKA limbs. The VM of the S-RAD TKA limb

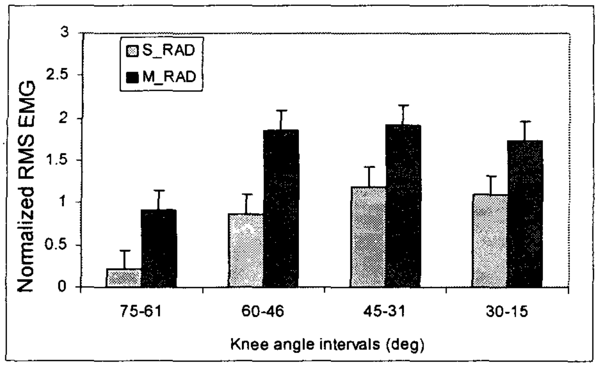

Fig. 6. Quadriceps muscle RMS EMG for 4 angle intervals from 75 degreesto 15 degrees of knee flexion during knee extension phase of sit-to-stand movement for TKA (top) limb. VM is shown above. For comparisons between TKA groups: * indicates $p< 0.05$, ** indicates $p < 0.01$.

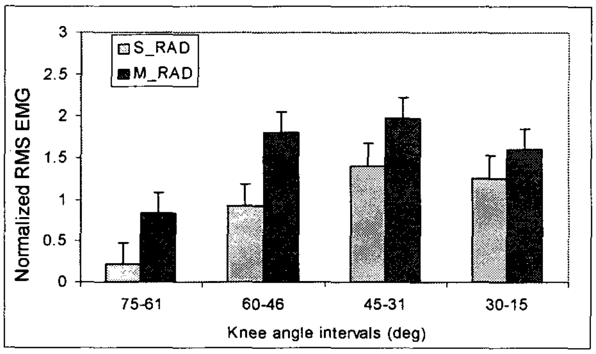

Fig. 7. Quadriceps muscle RMS EMG for 4 angle intervals from 75 degrees to 15 degrees of knee flexion during knee extension phase of sit-to-stand movement for TKA (top) limb. VL is shown above. For comparisons between TKA groups: * indicates $p < 0.05$, ** indicates $p < 0.01$.

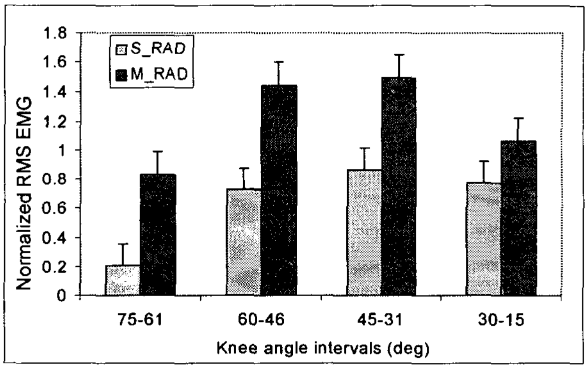

Fig. 8. Quadriceps muscle RMS EMG for 4 angle intervals from 75 degrees to 15 degrees of knee flexion during knee extension phase of sit-to-stand movement for TKA (top) limb. RF is shown above. Forcomparisons between TKA groups: * indicates $p < 0.05$, ** indicates $p < 0.01$.

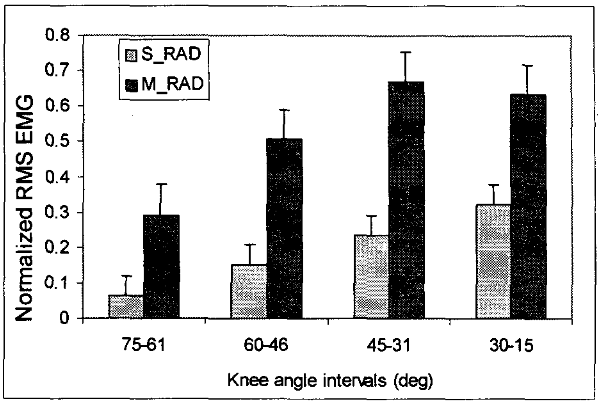

Fig. 9. Hamstring muscle RMS EMG for 4 angle intervals from 75 degrees to 15 degrees of knee flexion during knee extension phase of sit-to-stand movement for TKA (top) limb. BF is shown above. For comparisons between TKA groups: *indicates $p < 0.05$, ** indicates $p < 0.01$.

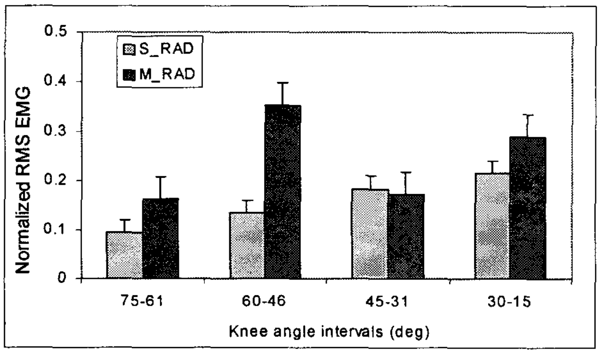

Fig. 10. Quadriceps muscle RMS EMG for 4 angle intervals from 75 degrees to 15 degrees of knee flexion during knee extension phase of sit-to-stand movement for TKA (top) limb. ST is shown above. For comparisons between TKA groups: * indicates $p < 0.05$, ** indicates $p < 0.01$.

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 Fig. 9-10 show the hamstrings EMG for the TKA and N-TKA limbs. As indicated in Fig. 9, 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 non-significant 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. 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. 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. As we mentioned earlier in the introduction, the multiple radii design of an M-RAD TKA could lead to knee mid flexion instability. In thissection, we will discuss the ABD/ADD displacement and hamstring co-contraction EMG that would reflect the stability of the TKA knee. 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 30ºof 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 wasnot surprising to see that the M-RAD TKA knee exhibited a distinctive ABD peak during the trunk flexion. It has been suggested that the hamstring co-contraction could stabilize the knee joint[5,7,11]. 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[5]. 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[9]. 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[11]. 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 jointin 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.

References

1. Berger, A., Riley, O., Mann, W., & Hodge, A. 1988. Total body dynamics in ascending stairs and rising from a chair following total knee arthroplasty. *Trans. 34th A. Mtg. Orthop. Res. Soc.*, 542.
2. Berman, T., Bosacco, J., & Israelite, C. 1991. Evaluation of total knee arthroplasty using isokinetic testing. *Clin. Orthop.* **271**, 106-113.
3. Dawson, D., Hendershot, G., and Fulton, J. 1987. Aging in the eighties. Functional limitations of individuals age 65 and over. **133**. *Hyattsville MD, Public Health Service. Advance Data From Vital and Health Statistics.*
4. Girgis, G., Marshall, L., & Monajem, A. 1975. The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. *Clin. Orthop.* **106**, 216-231.
5. Kasman, S., Cram, R., & Wolf, L. 1998. Knee Dysfunction. In G. S. Kasman, J. R. Cram, & S. L. Wolf (Eds.), *Clinical Applications in Surface Electromyography. Gaithersburg, Maryland. Aspen Publishers.* 363-389.
6. Riley, H. 1983. History and Evolution of Total Knee Replacement. Healy, W. L. Total Knee Arthroplasty, *A Comprehensive Aproach. Baltimore, MD, Williams & Wilkins.* **1-4.**
7. Solomonow, M., Baratta, R., Zhou, H., Shoji, H., Bose, W., Beck, C., & D'Ambrosia, R. 1987. The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. *Am. J. Sports Med.* **15(3)**, 207-213.
8. Thompson, W. 1989. Manual of Structural Kinestiology. (11 ed.). *St. Louis, Missouri: Times Mirror/Mosby College Pulishing.*
9. Wang, H., Simpson, K., Ferrara, M., Chamnongkich, S., Casto, S., & Mahoney, O. 2001. Does a multi-radius total knee arthroplasty knee function similar to a healthy knee. *XVIIIth Congress of International Society of Biomechanics.* 309-310
10. Wilson, N. 1993. Anatomy. *In W. N. Scott (Ed.), The Knee. St. Louis, Missouri: Mosby-Year Book, Inc.* 15-54.
11. Zhang, Q., & Wang, G. 2001. Dynamic and static control of the human knee joint in abduction-adduction. *J. Biomech.* **34(9)**, 1107-1115.

초록 : 앉았다 일어나는 동작동안 단축회전반경 무릎인공관절 수술자와 다축회전반경 무릎인공관절 수술자의 운동역학적 비교분석

진 영 완*
(동의대학교 레저스포츠학과)

단축범위 무릎인공관절 수술자와 다축범위 무릎인공관절 수술자를 대상으로 앉았다 일어나는 동안 운동학적 및 운동역학적 요인들을 비교분석한 결과는 다음과 같다. 앉았다 일어나는 동작은 다축범위 수술자 집단이 단축범위 수술자 집단보다 0.19초(p= 0.033) 빠르게 나타났다. 최대상체 굴곡각도는 다축범위 수술자 집단이 단축범위 수술자집단 보다 10°(p = 0.014)정도 크게 나타났다. 상체굴곡 각속도는 다축범위 수술자 집단이 단축범위 수술자 집단보다 7º • s^{-1} (p= 0.058)빠르게 나타났다. 단축범위 수술자 집단과 다축범위 수술자 집단의 ADD와 ABD의 차이는 거의 없었다. 대퇴사두근의 근전도분석은 내측광근은 무릎굴곡각 60º - 15º($p < 0.05$)에서 단축범위 수술자 집단 근전도 값이 다축범위 수술자집단 근전도값 보다 작게 나타났다. 외측광근은 무릎굴곡각 60º - 45º ($p < 0.05$)에서 단축범위 수술자 집단 근전도 값이 다축범위 수술자집단 근전도값 보다 작게 나타났다. 대퇴직근의 값은 무릎굴곡각 60º - 30º ($p < 0.05$)에서 단축범위 수술자 집단 근전도 값이 다축범위 수술자집단 근전도값 보다 작게 나타났다. 대퇴이두근의 값은 무릎굴곡각 75º - 15º ($p < 0.05$)에서 단축범위 수술자 집단 근전도 값이 다축범위 수술자집단 근전도값 보다 작게 나타났다.