

**THE EFFECT OF SINGLE RADIUS VERSUS MULTIRADIUS FEMORAL IMPLANT
ON KNEE FLEXION MOMENT DURING STAIR ASCENT**

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INTRODUCTION

Following total knee arthroplasty (TKA) for the treatment for osteoarthritis (OA), previous research has reported continual functional deficits one year post-TKA [24, 26]. Deficits often lead to the development and persistence of compensatory motions, often due to muscle weakness following TKA [4, 18, 23, 29]. Commonly referred to as quadriceps avoidance gait, increased sagittal trunk flexion decreases the demand of the knee extensor muscle group during activities of daily living [15, 22, 26]. Biomechanically, these compensatory motions manipulate the external knee flexion moment, often used to measure overall knee extensor function [2, 26]. However, knee strengthening rehabilitation protocols have not proven effective in regaining full strength within the first year following TKA [7, 18, 25], leading to the consideration of implant design as a possible limiting factor in overall post-TKA knee function [13, 18, 26, 29].

Anatomically, sagittal plane motion at the knee occurs around two different axes of rotation in the femur depending on joint angle [11]. From full extension to 10° of flexion, rotation occurs around the more anterior axis [11], allowing for smaller distance between the line of pull of the quadriceps and the implant's center of rotation [10, 11]. After approximately 10° to 30° of knee flexion, rotation shifts to the more posterior axis, which increases the distance between the line of pull and the center of rotation [10, 11, 16]. The multiradius (MR) femoral implant is widely used for its similarly changing center of rotation during flexion and extension. However, decreased knee extensor strength post-TKA has previously been suggested to result from rotation occurring around the anterior axis and subsequently shortened lever arm during knee motion [3, 16, 22-24]. In contrast, the single radius (SR) implant is designed with only one fixed posterior axis of rotation. The design of the SR implant may provide a better mechanical advantage throughout the entire knee range of motion, thus improving the function of the extensor muscle group during activities of daily living requiring greater knee flexion angles [1, 3, 5-7, 30], such as stair ascent [2, 28].

A majority of studies evaluating the SR implant demonstrate greater knee flexion angles, improved subjective clinical scores, and decreased compensatory motions compared to the MR implant [1, 5, 6, 16, 22, 30]. Although SR is theoretically more functionally advantageous when compared to the MR implant, these results are based on clinical evaluations and not biomechanical analysis. Additionally, previous studies are limited to double limb support tasks [2, 18, 26], such as chair rising, in which the demand of the exercise may limit the ability to

detect multiple functional deficits between implants compared to single limb activities. Therefore, the purpose of this study is to compare knee flexion moment and sagittal trunk flexion, during stair ascent, and knee extensor strength between patients receiving SR and MR implants at pre-TKA and at six weeks and three months post-TKA.

METHODOLOGY

Participants

A randomized, longitudinal design was used to examine the gait biomechanics of osteoarthritic patients within two weeks prior to total knee arthroplasty (TKA) and post-TKA at six weeks and three months. Inclusionary criteria included: 1) under 75 years of age, 2) no previous history of lower extremity fracture, osteotomy, or joint replacement, 3) undergoing a unilateral or bilateral TKA for the treatment of OA, and 4) ability to walk without an aid. The same board certified orthopedic surgeon screened each patient and performed all TKA procedures. Before enrollment to participate, all patients completed the informed consent process and signed consent forms approved by the Institution's Institutional Review Board.

Two TKA implant designs were included for comparison within this study. Patients who were screened for inclusion within the study and underwent the first data collection prior to surgery were randomly allocated to receive either a SR implant (GetAroundKnee™, Stryker Orthopedics, Mahwah, NJ) or a MR implant (Balanced Knee® System, Ortho Development Corporation, Draper, UT).

Instrumentation

All biomechanical analyses were conducted at the University of Hawai'i Gait Laboratory. Upon arrival, anthropometric data, including age, weight, height, leg length, and knee and ankle joint width, were collected prior to stair ascent trials. A GPM anthropometer (SIBER & Hegner, Zurich, Switzerland) for joint width, DETECTO Certifier scale for measuring body mass (Webb City Mo, USA), wall-mounted stadiometer for height (Model 67032, Seca Telescopic Stadiometer, Country Technology, Inc., Gays Mills, WI, USA), and Dritz 60 inch measuring tape were used to collect the anthropometric data. The UCLA Activity Score, an ordinal survey from 1-10 to describe activity level, was used to assess self-reported overall functional ability [19]. Higher UCLA scores indicate a higher amount of rigorous activity level, with choice #10 stating:

“Regularly participates in impact sports.” The chair rising question, “How does your knee affect your ability to rise from a chair?” was used to assess knee function, with the following possible choices in ordinal order: 1) “Because of my knee I cannot rise from a chair,” 2) “Because of my knee, I can only rise from a chair if I use my hands and arms to assist,” 3) “I have pain when rising from the seated position, but it does not affect my ability to rise from the seated position,” and 4) “My knee does not affect my ability to rise from a chair” [21]. A 3D motion capture system and Nexus Software (Vicon, Inc. Centennial, CO) was used to collect stair ascent kinematics with 29 retro-reflective markers and four arrays placed in accordance with the laboratory model. Each array consisted of a square pad with four retro-reflective markers set in a distinct pattern to represent the specific right and left leg segment. Single markers were placed on the spinous process of the seventh cervical vertebra and tenth thoracic vertebra, right inferior scapular angle, jugular notch, xiphoid process. Bilateral markers were placed on the acromion process, anterior superior iliac spine, posterior superior iliac spine, medial and lateral knee epicondyles, medial and lateral malleoli, calcaneous, base of the fifth and head of the first, second, and fifth metatarsals.

Stair ascent protocol was based on that performed by Vallabhajousla et al. [28]. Stairs included three steps with dimensions of 18 cm step rise, 46 cm step width, and 28 cm step tread [28]. Ground reaction forces (GRF) of the involved limb were measured using two force plates (Advanced Mechanical Technology Incorporated Boston, MA), one embedded flush with the floor located just prior to beginning the stair ascent and the second embedded within the second step of the stairs to measure the involved limb during stair ascent. Kinematic data was collected at 240 Hz and time synchronized with kinetic data collected at 960 Hz. Raw, unsmoothed kinetic data was utilized for all kinetic measures except for joint moments which was calculated using inverse dynamics based on marker trajectories and kinetic data which were both smoothed with a Butterworth filter using a 10 Hz cut-off. All kinematic and kinetic data were processed using Visual 3D (C-motion Inc., Germantown, Maryland).

Procedure

Five successful stair ascent trials were collected unless the patient was unable to complete the required trials. Patients began by taking three steps before ascending the stairs at a self-selected speed [28] and progress up the stairs, making contact with only one foot on each

subsequent step. After reaching the top platform, the patient continued with one additional step to verify that a natural gait continued through the last step and deceleration did not occur. Handrails were provided for safety, but patients were instructed to not use them unless balance was compromised. Trials with handrail usage were discarded. A member of the research team was positioned at the bottom of the stairs at all times to assist if needed. Due to high intra-subject variability previously reported during stair climbing in the OA population, successful trials were averaged.

Following the stair trials, bilateral muscle torque for knee extension was measured with a Microfet2 hand held dynamometer (HHD) (Hoggan Health Industries, West Jordan, UT) in a gravity dependent position. The HHD was secured with a strap to the anterior shank at 80% of the distal length. The patient was placed in a short-seated position with an angle of 155° between the trunk and thigh segment and 65° of knee flexion. Instructions were given to the patient to extend their knee and build to maximum extension contraction over three seconds and to hold a maximal contraction for an additional two seconds. Patients were also instructed to extend their knee without extending or flexing their trunk. Two trials were recorded with at least 30 seconds of rest in between. A third trial was completed if the peak value of the two trials were not within 10% of each other. Strength testing was terminated upon subject request if pain became limiting.

Statistical Analysis

Due to missing values from the inability to complete ascent at certain data collection periods, dependent *t*-tests were performed for each dependent variable over time, compared to pre-TKA levels. Additionally, independent *t*-tests were performed to compare dependent variables between implant groups at each time period. Pearson's correlation coefficients were used to determine the relationship between sagittal plane dependent variables and knee extensor strength. Individual joint kinetics were reported as external moments.

RESULTS

Eight patients (nine knees) received the MR implant and five patients (eight knees) received the SR implant in this study. Demographics, including age (65.3 ± 5.4 years old), body mass (77.4 ± 12.6 kg), and height (1.65 ± 0.09 m), were not significantly different

between groups. One MR patient was unable to perform stair ascent prior to surgery, and data from one SR knee prior to surgery was discarded due to technical errors. Therefore, data were collected from eight MR knees and seven SR knees at pre-TKA. Due to the inability to ascend stairs or to attend the data collection due to pain, the six week post-TKA data collection included four MR patients (five knees) and five SR patients (eight knees), and the three month post-TKA data collection included seven MR patients (seven knees) and four SR patients (seven knees).

No significant difference in knee flexion moment was present between implants at pre-TKA (MR= 0.62 Nm/kg, SR= 0.50 Nm/kg, p= 0.47). Knee flexion moment in MR implants was significantly greater than SR implants at six weeks post- TKA (MR= 0.59 Nm/kg, SR= 0.28 Nm/kg, p= 0.049) but was not significantly different at three months post-TKA (MR= 0.39 Nm/kg, SR= 0.47 Nm/kg, p= 0.38). Over time, knee flexion moment in the SR implants significantly decreased at six weeks post-TKA compared to pre-TKA (p= 0.02), but was not significantly different at three months post-TKA compared to pre-TKA (p= 0.52). In MR implants, knee flexion moment was not significantly different at six weeks (p=0.09) or three months post-TKA (p=0.59) compared to pre-TKA (Table 1).

Table 1. Knee Flexion Moment (Nm/kg)

	MR		SR	
Pre-TKA	0.62	± 0.36	0.50	± 0.24
Post-TKA				
6 weeks	0.59	± 0.37*	0.28	± 0.12*^
3 months	0.47	± 0.21	0.39	± 0.13

Means ± Standard Deviations

TKA=Total Knee Arthroplasty

MR= Multiradius; SR= Single Radius

Nm/kg= Newton Meter per Kilogram

*= Significantly Difference Between Implants

^= Significantly Different than Pre-TKA

No significant difference in knee extensor strength was present between implants at pre-TKA (MR= 58.3 ft-lb, SR= 62.9 ft-lb, p= 0.77). Knee extensor strength in MR implants was significantly greater than SR at six weeks post-TKA (MR= 64.4 ft-lb, SR= 34.2 ft-lb, p= 0.04) but was not significantly different at three months post-TKA (MR= 49.3 ft-lb, SR= 56.3 ft-lb, p= 0.45). Over time, knee extensor strength in SR implants significantly decreased at six weeks post-TKA compared to pre-TKA (p= 0.04) but was not significantly different at three months post-TKA compared to pre-TKA (p= 0.14). In the MR implants, knee extensor strength was not

significantly different at six weeks (p=0.26) or three months post-TKA (p=0.49) compared to pre-TKA (Table 2).

Table 2. Knee Extensor Strength (ft-lb)

	MR		SR	
Pre-TKA	58.27	± 31.56	62.94	± 27.40
Post-TKA				
6 weeks	64.37	± 36.30	34.16	± 08.45*^
3 months	49.29	± 16.52	56.33	± 17.30

Means ± Standard Deviations

TKA= Total Knee Arthroplasty

MR= Multiradius; SR= Single Radius

ft-lb= Foot per Pound

*= Significantly Difference Between Implants

^= Significantly Different than Pre-TKA

There were no significant differences in sagittal trunk flexion between implants at pre-TKA (MR= 29.2°, SR= 25.6°, p= 0.25), six weeks (MR= 26.5°, SR= 29.3°, p= 0.51), or three months post-TKA (MR= 27.6°, SR= 25.5°, p= 0.54). Over time, sagittal trunk flexion in SR implants significantly increased at six weeks post-TKA compared to pre-TKA (p= 0.002), but was not significantly different at three months post-TKA compared to pre-TKA (p= 0.75). In the MR implants, sagittal trunk flexion was not significantly different at six weeks (p= 0.63) or three months post-TKA (p= 0.41) compared to pre-TKA (Table 3).

Table 3. Trunk Flexion Angle (°)

	MR		SR	
Pre-TKA	29.22	± 5.95	25.59	± 5.60
Post-TKA				
6 weeks	26.52	± 7.06	29.31	± 7.22^
3 months	27.54	± 7.02	25.46	± 5.10

Means ± Standard Deviations

TKA= Total Knee Arthroplasty

MR= Multiradius; SR= Single Radius

°= Degree

*= Significantly Difference Between Implants

^= Significantly Different Than Pre-TKA

The UCLA scores for patients with MR implants were significantly greater than those receiving SR at pre-TKA (MR= 5.6, SR= 3.7, p= 0.001) and at six weeks post-TKA (MR= 5.4, SR= 3.8, p= 0.003) but was not significantly different at three months post-TKA (MR= 4.9, SR= 4.4, p= 0.55). The UCLA scores of SR implants were not significantly different at six weeks (p=

1.0) or three months post-TKA ($p= 0.36$) compared to pre-TKA. Over time, the UCLA scores of MR implants were not significantly different at six weeks ($p= 0.18$) or three months post-TKA ($p= 0.61$) compared to pre-TKA. The Chair Rising Questionnaire scores were not significantly different between implants at pre-TKA (MR= 3.1, SR= 2.6, $p= 0.10$). Over time, the Chair Rising Questionnaire scores in MR implants were significantly greater than SR at six weeks (MR= 3.8, SR= 2.8, $p= 0.002$) but was not significantly different between implants at three months post-TKA (MR= 3.3, SR= 3.3, $p=1.00$). The chair rising questionnaire scores of SR implants were not significantly different at six weeks post-TKA ($p= 0.36$), but significantly increased at three months post-TKA compared to pre-TKA ($p= 0.02$). In the MR implants, chair rising questionnaire scores were not significantly different at six weeks ($p= 0.06$) or three months post-TKA ($p= 0.61$) (Table 4).

Table 4. Questionnaire Scores

	UCLA					Chair Rising Questionnaire				
	MR		SR		MR		SR			
Pre-TKA	5.6	± 0.5*	3.9	± 1.1*	3.1	± 0.6	2.6	± 0.5		
Post-TKA										
6 weeks	5.4	± 0.9*	3.8	± 0.7*	3.8	± 0.4*	2.8	± 0.5*		
3 months	4.9	± 1.5	4.4	± 1.1	3.3	± 0.8	3.3	± 0.5^		

Means ± Standard Deviations

Maximum UCLA score= 10; Maximum Chair Rising Questionnaire score = 4

TKA= Total Knee Arthroplasty

MR= Multiradius; SR= Single Radius

*= Significantly Different Between Implants

^= Significantly Different than Pre-TKA

Knee flexion moment and knee extensor strength in MR implants were significantly correlated at pre-TKA ($r= 0.708$, $p= 0.049$) and at six weeks post-TKA ($r= 0.967$, $p= 0.007$) but not significantly correlated at three months post-TKA ($r= 0.415$ and $p= 0.36$). Knee flexion moment and knee extensor strength in SR implants were not correlated at pre-TKA ($r= 0.282$; $p= 0.54$), six weeks ($r= -0.032$; $p= 0.93$), or three months post-TKA ($r= -0.167$; $p= 0.72$) (Table 5).

Table 5. Correlations (r) to Knee Extensor Strength

	Sagittal Trunk Angle		Knee Flexion Moment	
	MR	SR	MR	SR
Pre-TKA	-0.681	-0.695	0.708*	0.282
Post-TKA	-0.499	-0.499	0.823*	0.187

TKA= Total Knee Arthroplasty

MR= Multiradius; SR= Single Radius

*= Significance (p <0.05)

DISCUSSION

The results of the current study revealed a significant decrease in knee flexion moment, an indicator of the activity knee extensor mechanism during functional activities, between pre-TKA and six weeks post-TKA for SR implants but not MR implants. This early difference may indicate that those receiving an MR implant may not experience significant decreases in function immediately following surgery and may return to a more normal gait pattern sooner than those with a SR implant. However, no significant difference in knee flexion moment was present at three months post-TKA between the two implant designs. Despite the lack of difference, deficits for both implants were still present at three months, as neither implant reached pre-TKA function levels. As most patients had finished physical therapy by the three month data collection, this finding supports the need for more prolonged rehabilitation following TKA.

Previous research has suggested that SR implants produce a more efficient extensor mechanism post-TKA [3, 22, 31]. In the present study, similar to knee flexion moment, knee extensor strength in SR implants also demonstrated a significant decrease at six weeks post-TKA, but was no longer significantly different at three months post-TKA compared to MR implants. These result also conflict previous literature that examined knee extensor strength, which is possibly due to differences in methodologies [6, 22, 30]. Despite these inconsistencies, the early deficits in SR implants may be a cause for concern, as compensatory motions could lead to abnormal forces on the implant immediately following surgery.

The most noticeable compensatory motion was sagittal trunk flexion, which commonly occurs during gait when quadriceps weakness is present. As seen in the patients with SR implants in the current study, forward trunk flexion moves the center of mass forward, resulting in a decrease in knee flexion moment [26]. Compared to pre-TKA, only the SR implants had

significantly greater sagittal trunk flexion at six weeks post-TKA, indicating a greater compensatory pattern when compared to MR implants. This finding is contrary to previous research, in which the MR implants have been shown to have greater compensatory motions when rising from a chair [16, 30]. The difference in results could be due to the difficulty of the task performed, as rising from a chair allows a patient to remain in double support during the entire task. However, stair ascent requires single support, demanding greater strength and balance, which could increase the need for compensatory motions when overall function is lacking. Therefore, the greater knee extensor strength, and the subsequent decrease in compensatory motions, in the MR implant compared to the SR implant may be an indication of greater function immediately following surgery.

Both UCLA and chair rising questionnaire scores in MR implants were significantly higher than scores in SR implants at six weeks post-TKA but were no longer significantly different between implants by three months post-TKA. These findings are contradictory to previous research of which showed greater functional scores in SR implants [1, 6]. The current study revealed that the UCLA scores were significantly higher in MR implants when compared to SR implant prior to TKA. It is possible that the increased functional scores at six weeks post-TKA may be a result of the higher functional ability pre-TKA in those who received MR implants.

The results of the current study are clinically applicable when comparing MR and SR implants but limitations were present in the current study. In the MR group, only one of eight patients underwent bilateral TKA whereas in the SR group, three of five underwent bilateral TKA. Functional differences caused by unilateral versus bilateral TKA may substantially account for the significantly different knee flexion moment, knee extension strength and sagittal trunk flexion between groups at six weeks in the present study. Further, by restricting the use of handrails during stair ascent, variability in compensatory motions, such as swing leg circumduction and lateral trunk leaning, were present but not consistent between patients or trials. Additionally, the small sample sizes for each implant also serves as a limitation in this study. These two limitations lead to high standard deviations, possibly limiting the ability to find significant differences.

CONCLUSION

Deficits in knee extensor strength and lower function scores led to reduced overall knee function and increased compensatory motions in the SR implants at six weeks post-TKA compared to MR implants, indicated by the decreased knee flexion moment and greater sagittal trunk flexion during stair ascent. However, these deficits were no longer present by three months post-TKA, as no significant differences in function or strength were noted between SR and MR implants. It was concluded that despite the possibility of early functional differences related to implant design, by three months post-TKA, the choice of MR or SR implant did not significantly influence the function of patients following TKA.

REVIEW OF LITERATURE

Knee Osteoarthritis and the Influence of Gait

Introduction

The degenerative pathology of a joint's protective cartilage is known as OA [14], and most commonly occurs at the knee joint [4, 14, 32]. Previous research has indicated that in addition to knee malalignment and pain [20], compensatory gait mechanics became prevalent as a result of worsening knee OA. Osteoarthritic patients often presented with timing alterations during the phases of gait [14], and less range of motion and smaller flexion moments in the sagittal plane compared to healthy controls [4]. These gait deviations, therefore, may affect functional ability and activities of daily living in this population [32].

Review of Literature

Uyen-Sa et al. investigated the prevalence of knee pain and symptomatic knee osteoarthritis. The researchers used a cross-sectional approach using six National Health and Nutrition Examination Surveys (NHANES) and Framingham Osteoarthritis (FOA) studies in regards to previous knee pain and symptomatic knee OA over 20 years [20]. NHANES surveys were conducted in waves from 1971-1975, 1976-1980, 1988-1994, and continuous NHANES from 1999-2000, 2001 -2002, and 2003-2004. 1382, 4342, 3682, 1066, 1011, and 1054 participants were included for the six NHANES, respectively [20]. Knee pain in the FOA Study was examined three times at approximately ten years apart. Participants were classified with symptomatic knee pain if they responded positively to having knee pain within the past 12 months [20]. Radiographically, the Kellgren-Lawrence scale of 0 to 4 was utilized based on the presence of osteophytes, joint space narrowing, sclerosis, attrition, and cysts in the anterior-posterior view, and a score of two or greater indicated OA symptoms [20]. Marginal standardization with logical regression was calculated to estimate the standardized prevalence of knee pain from the NHANES and FOA study, and radiographic and symptomatic knee OA from the FOA study [20]. Results revealed that knee pain has doubled over 20 years in women and tripled in men, but the prevalence of radiographic knee OA results did not increase before or during the FOA study [20]. The authors conclude that there is an increase of symptomatic knee OA and prevalence of knee pain [20]. The reasoning for increase in symptoms, but not in

radiographic OA cannot be easily explained as determined by the researchers, but they proposed that the increase of knee pain and symptoms might serve as an explanation for the increase in TKA surgeries performed [20].

Unlike Uyen-Sa et al. who examined OA symptoms, Kotti et al. analyzed ground reaction force (GRF) on the knee in participants with OA. This study was completed to determine if walking data can accurately predict if diagnosed OA is present [14]. There were 47 patients, out of 180, who diagnosed with OA based on radiographic findings and recruited from the various regional hospitals that participated in the study [14]. Average age of the no knee OA and knee OA groups were 45.0 and 58.1 respectively [14]. The patients completed a maximum of three trials to cleanly strike the force plate during a 6 m walk, which consisted of two force plates embedded to record the force of the left and the right [14]. Vicon Nexus software at 1000 Hz sampling rate was utilized for recording [14]. Subjects displayed the lowest GRF in the anterior-posterior axis, but higher values were seen in the medial-lateral and vertical axes compared to the patients without OA [14]. The GRF was also not strictly symmetrical over the two legs, and the authors believed it may be due to random signals from the nervous system to coordinate motion [14]. Normal subjects displayed an extended time in stance phase compared to the OA participants [14]. The 36 Principal Components utilized resulted with a specificity of 0.79 and sensitivity of 0.77 with a precision of 0.97 and accuracy of $82.62 \pm 13.75\%$ [14]. The authors determined that based on the movement patterns that resembled patterns observed in OA patients and the high number of false negatives, they were able to recognize patients who believed they were healthy, but actually had OA [14]. The authors suggested that movement patterns are distorted in a systematic pattern when a pathology is present [14].

Deluzio and Astephen also investigated the biomechanical features related to knee osteoarthritis, particularly using analyzing temporal gait waveforms at specific joint measures with dynamic flexion [4]. Their study included 50 elderly participants with OA prior to TKA surgery and 63 asymptomatic volunteers serving as control [4]. Data was collected in five walking trials at self-selected pace in regular walking shoes, while optoelectronic gait analysis system for radiographic technique studied the 3D gait patterns [4]. Principal component analysis, as used in the study by Kotti et al., was calculated to summarize the most important information in the data, as described by the authors, in the entire gait cycle to explain maximal amounts of variances in the original variables [4, 14]. Particularly, data was interpreted by

scoring each feature (PC score) to the corresponding waveform shape degree for each participant [4]. Results revealed significantly less range of motion during the gait cycle in the OA group with knee flexion during late stance and mid-swing of the gait cycle, with a large difference between the amount of knee flexion during late stance and mid-swing compared to control [4]. The OA group was also less flexed throughout the gait cycle compared to the control represented by the results of PC1 [4]. Flexion moment overall was lower during stance compared to the control group, and the OA patients also had a higher adduction moment [4]. Conclusions were made that the smaller knee flexion moment, larger adduction moment, as well as smaller knee flexion angle range throughout gait were important differences seen in the OA group compared to the control [4]. The authors explained that the range of knee flexion motion is more important than overall knee flexion angle magnitude in knee osteoarthritis individuals [4]. There was no significant variation in the pattern of kinetic knee waveforms between subjects, and the authors decided that it may be impossible to define some parameters for all subjects in a pathological study [4]. This is due to the difficulty with determining whether the gait pattern differences may be a result from a contributing factor of OA, and the need.

Zeni et al. also used the Kellgren-Lawrence score, as seen in Uyen-Sa et al., to examine participants and the predictability of having TKA treatment for end-stage knee OA [20, 32]. The end stage of knee OA was defined as radiographic evidence of OA in more than one compartment when the Kellgren-Lawrence score was greater than or equal to three. There were 120 patients, 59 males and 61 females, ranging from 28 to 83 years old, whereas forty subjects, 46-78 years old, chose to have TKA within two years, since the initial physical therapist (PT) evaluation [32]. All participants presented concerns for knee pain during daily activities that prompted them to consult an orthopedic surgeon and have an evaluation completed by a PT. A functional evaluation, referred to as the Delaware Osteoarthritis Profile, by a PT included measured height, weight, quadriceps strength, active knee range of motion, self-perceived functional ability, functional mobility, and ability to negotiate stairs [32]. Quadriceps strength was measured in volitional force produced during unilateral isometric knee extension performed in KinCom dynamometer with knees at 75°, hips at 90° [32]. Active range of motion included flexion and extension of the knee joint measured by a goniometer, and the Knee Outcome Score - Activities of Daily Living Subscale (KOS-ADLS) was distributed. Functional mobility tests included two averaged trials of the Timed Up and Go (TUG) and timed Stair Climbing Task

(SCT). TUG required subjects to rise from a chair, walk 3 meters, turn around, and return to the seated position with the option to use their arms with to sit and stand, while the SCT, subjects began at the bottom of a flight of 12 stairs, turned around and descend the stairs [32]. Subjects who were significantly older had significantly slower TUG and SCT times [32]. Patients that underwent TKA showed significant weakness in both limbs, lower self-reported functional ability, and less knee extension when compared to the control [32]. Logistic regression calculated that age, KOS-ADLS, TUG, SCT, quad strength and knee extension were significantly accurate predictors for TKA surgery completion within two years [32]. Age, knee extension, and KOS-ADLS together significantly predicted whether or not a person would undergo TKA, but was a better predictor for those who would not undergo TKA [32]. Younger age, higher KOS-ADLS scores, faster TUG and SCT times, stronger quad and full knee extension predicted those who did not undergo TKA at a 91% correct prediction rate [32]. The risk of undergoing TKA increased at odds ratio values of 1.13 and 1.23 for every one-year increase in age and every degree of knee flexion contracture respectively [32]. These potential risk factors, as discussed by the authors, can be addressed to postpone the need for TKA [32].

Conclusion

Previous research has concluded that common findings of knee OA include knee pain, gait abnormality, decrease in functional ability reported, and that patients commonly presented with a shortened stance phase [14]. Patients with OA also presented with decreased movement in the sagittal plane, but a greater adduction angle along the horizontal plane in the involved knee [4]. Additionally, patients with more severe OA frequently presented with more pronounced symptoms [20], significantly effecting activities of daily living, knee range of motion, and extensor strength. The effects of OA on the knee have indicated the need for TKA surgery [32].

Knee Extensor Strength and Function at Post-Total Knee Arthroplasty

Introduction

Previous research has commonly reported diminished knee extensor muscle strength, lower functional ability, and lower activity questionnaire scores compared to healthy control knees at post-TKA [18, 19, 25]. Multiple studies have also reported that the knee extensor muscles, such as the quadriceps, may return to pre-TKA strength levels at six months after

surgery, but strength remained significantly less than the uninvolved limb and healthy control knees [15, 23, 25]. With diminished quadriceps strength, functional activities including stair ascent, walking fast, and getting up from a chair became more difficult and limited within this population [18, 21, 29]. Functional ability was also measured through activity questionnaires in addition

Review of Literature

Results have shown that quadriceps weakness is a typical result that affect functional activities. Lorentzen et al. examined the early changes in isokinetic and isometric strength in knee flexor and extensors after TKA surgery [15]. Thirty participants were recruited from three hospitals in Copenhagen who received single leg TKA due to primary arthrosis. The participants received standard postoperative treatment while in the hospital by a physiotherapist, but no treatment was given afterwards [15]. A pain rating scale for pain at night, rest, walking, and overall worst pain as well as range of motion and Lequense index for knee arthrosis were completed [15]. Bilateral muscle strength for extension and flexion at the knee at speeds of 30°/s and 120°/s for isokinetic measurements were performed, with peak torque at 75° was recorded using the Cybex 6000 Dynamometer [15]. These measurements were performed at one-week pre-TKA, and three months and six months post-TKA. The authors recorded that the surgical knees had a reduction in pain and disability degree, but a decrease in motion, specifically, pre-TKA, and three months and six months post-TKA for range of motion were 118°, 95° and 100°, respectively [15]. Isokinetic muscle strength for flexion increased by 30% and 53% at both angle velocities of 30°/sec and 120°/sec respectively, but the uninvolved leg at six months post-TKA still presented higher flexor strength at both velocities [15]. Isokinetic extensor strength significantly increased 18% and 14% for 30°/s and 120°/s respectively, in the involved leg [15]. Isometric flexion peak torque significantly decreased by 17% in the involved knee, while extension peak torque remained decreased at three months, but returned to preoperative levels at six months post-TKA [15]. Both torque values were significantly lower than the uninvolved leg [15]. Despite the improved results and diminished AKP seen post-TKA, all flexion and extensor strength were significantly less than the uninvolved limb and healthy control values [15].

In a study by Silva et al., results of significantly lower strength was seen in TKA patients compared with healthy age, BMI matched controls [23]. Participants included 52 control knees

compared to 32 TKA knees at two years post-TKA, a time period that was not seen in Lorenzten et al [15]. Participants were set up in a LIDO Active Dynamometer model 200 to measure isometric peak extension and flexion torques, measured from 0° to 90° of knee flexion at seven positions of 15° increments. A computer monitor displayed a real-time column graph of generated torque, available for participants to observe while they performed three seconds of maximal knee extension at each position, followed immediately by three seconds of maximal knee flexion [23]. The authors used a step-wise multivariate analysis to adjust for patient characteristics and a 2-sample Student's *t*-test to compare differences between groups [23]. Isometric extension torque was highly variable and was significantly lower than control participants at all points, in particular at time points closest to full extension. The hamstring: quad ratio also increased with knee extension. There was a strong correlation between these two variables, isometric extension torque and hamstring: quad ratio, with Knee Functional Society Score [23]. The authors suggest that this may be due to muscle atrophy from disuse of the leg before TKA, which did not fully recover post-TKA [23]. Adequate extensor mechanism function is also a prerequisite for common activities of daily living, such as stair ascent, which the authors provided as a logical explanation to the correlation [23]. Additionally, the authors recorded that women, older participants, and relatively obese women tended to have higher isometric hamstring: quad ratio and relatively lower quadriceps strength [23]. The authors concluded that based off of their findings, more aggressive rehabilitation is required to restore knee extension, particularly with relatively obese women [23].

Stevens-Lapsley et al. compared co-activation and strength of the quadriceps to the hamstring for unilateral TKA to the non-operative leg and a control group in a study [25]. Ranging from 50 to 85 years old, 13 women and 17 men were measured and compared to 15 healthy controls for the appropriate sample size [25]. These participants had inpatient rehabilitation at the hospital and two weeks of home physical therapy post-TKA that focused on quadriceps and hamstring muscle strength [25]. Standardized surgical procedure, progressive exercises, and rehabilitation timelines were implemented to control for confounding factors. Quadriceps and hamstring strength was measured with an electromechanical dynamometer with 60° of knee flexion with visual and verbal feedback [25]. Unlike the study completed by Lorenzten et al., these authors also used EMG to measure maximal voluntary isometric contraction for co-activation measurement [15, 25]. A Visual Analogue Scale was distributed

for both legs, which was completed two weeks pre-TKA and one month, three months, and six months post-TKA [25]. Quadriceps and hamstring comparisons revealed no significant difference of strength loss [25]. Both muscles were significantly weaker compared to the control [25]. At one-month post-TKA, quadriceps and hamstring strength decreased 51.56% and 48.43% respectively, but the quadriceps continued to remain weaker than the uninvolved leg at six months post-TKA [25]. Hamstring strength at six months post-TKA was not significantly weaker than the uninvolved leg, but was weaker than the control [25]. Co-activation was also significantly greater at one-month post-TKA legs compared to the uninvolved, which continued three to six months without statistical significance [25]. Hamstring strength was stronger than quadriceps comparatively, but both were significantly weaker than the control [25]. The strength deficit between these two muscles may be further magnified during co-activation during weight bearing activities [25]. The authors discussed a need for increased functional stability of the knee with these activities, but this abnormal co-activation may result in muscle weakness, wearing of the implant, and increased pain [25]. Therefore, the researchers emphasized the importance of hamstring and quadriceps strengthening rehabilitation based upon the persistent deficiencies recorded, and that further research in strength with dynamic and functional movement should be completed [25].

Walsh et al. examined physical impairments and functional limitations of individuals one year post-TKA compared to gender and age matched controls [29]. Muscle strength defined for this study was peak torque (Nm) developed during five maximal contractions [29]. Isokinetic knee extensor and flexor endurance was determined by total work during 15 concentric contractions at angular velocities of 90°/s and 120°/s [29]. The TKA group consisted of 13 women and 16 men, eight who had bilateral TKAs, who were assessed approximately one year post surgery [29]. Concentric isokinetic knee torque and total work evaluated by a preset LIDO Active isokinetic dynamometer as similarly measured in the study by Lorentzen et al. [15, 29]. Functional tests included a self-paced walk of 160 m at a “normal pace,” and a “fast pace but without overexertion,” as described to the participants by the researchers [29]. A questionnaire recall on physical activity including household, sporting, and leisure activities were distributed. Also conducted was a timed stair-climbing test that included HR, pain, and perceived exertion during ascending and descending one flight of 10 steps [29]. Subjects had knee AROM of less than or equal to 90° of flexion which is adequate for everyday function, but an extension loss of

about 10° compared to the control group [29]. Besides self-paced walking pain scores, no results showed significant differences. Both mean peak torque at 90°/s and 120°/s of extensor and flexor strength were below the values of the control and uninvolved limb for males and females [29]. Both involved and uninvolved limbs also had decreased work with extension and flexion, and less work was produced at the 120°/s angular velocity [29]. Greater extensor and flexor strength in the uninvolved limb were demonstrated in both males and females, but remained at about 73% and 88% of the strength compared to controls, respectively [29]. The TKA group achieved over 80% of the normal and fast walking speeds of their control counterpart, with similar heart rate, but stair climbing performance of the TKA group was completed in more than twice the amount of time ascend and descend compared to control, and females additionally reported increased pain and exertion compared to males [29]. The authors concluded that although females with TKA had greater functional limitations of stair climbing tests, males with TKA had smaller deficits during stair climbing test but larger decrease in muscle strength and local muscular endurance [29].

Mizner et al. also examined quadriceps strength post-TKA with functional activities. Strength was correlated with sit-to-stand (STS), TUG, SCT and six minute walk test (6MW) [18]. STS was analyzed via Vicon 3D with six-camera motion analysis, while patients were timed at a pace that was described as “quickly and safely as possible” during TUG and SCT tests [18]. The 6MW test consisted of participants walking as many laps as possible within 6 minutes [18]. Quadriceps strength testing was completed by dynamometer with the hip at 90° and knee at 75° of flexion, along with a numeric rating scale for knee pain [18]. Electromyography was also recorded to measure strength of the quadriceps, gastrocnemius, anterior tibialis, and hamstring, along with Quadriceps Index for knee torque measurement for quadriceps strength for force production [18]. Participants included nine men and five women ranging from 53 – 74 years old at three months post-TKA [18]. Subjects received six weeks of outpatient physical therapy that was aimed at pain and swelling control, improving knee range of motion, muscle strength, and functional ability [18]. The involved leg was compared to their bilateral, uninvolved leg. Results revealed that quadriceps strength of both the uninvolved and involved leg had a negative correlation with SCT time and a positive correlation with 6MW distance traveled [18]. The uninvolved leg had a significant negative correlation with TUG time completion, while the involved leg did not significantly correlate with time to complete TUG [18]. There was no

significant difference with heel strike with knee flexion, but average peak knee flexion angle during weight acceptance showed significantly lower difference in the uninvolved limb, while knee excursion revealed significantly lower results for the involved limb [18]. The involved leg also had a significantly lower average peak vertical ground reaction force compared to the uninvolved [18]. Knee extension moment was not significantly different between knees, and quadriceps strength in the involved leg negatively correlated with time to complete SCT, and positively with distance traveled on the 6MW [18]. Quadriceps weakness was present post-TKA at three months, and function was also significantly decreased which is seen even stronger in the uninvolved [18]. The authors suggested this may be due to the asymmetry in knee excursion with weight acceptance in the gait phase, and potentially for compensation for bilateral support in some of the activities, such as STS [18]. This compensation may also serve as a causative factor for the lesser amount of ground reaction force with the involved leg [18]. The authors discussed that quadriceps strength may improve beyond the three month assessment, but there is a definite quadriceps weakness postoperatively that may be affecting functional movement [18].

Nylan et al. also examined stair climbing and extensor strength and patient perception of their ability to rise from a chair, as seen in the previous study by Mizner et al. [18]. The intended purpose was to identify a simple and safe method for determining when to begin stair-climbing during early post-TKA rehabilitation, with the hypothesis that those who perceived their chair-rise ability as poor would also display poor stair climbing ability and weaker quadriceps strength [21]. These patients were all given a progressive home based therapeutic exercise program. Unilateral TKA Patients at three to four weeks post-TKA answered the question to the KOS-ADLS question: “How does your knee affect your ability to rise from a chair?”[21]. Patients chose from four possible response: (1) “Because of my knee, I cannot rise from a chair,” (2) “Because of my knee, I can only rise from a chair if I use my hands and arms to assist,” (3) “I have pain rising from the seated position, but it does not affect my ability to rise from the seated position,” (4) “My knee does not affect my ability to rise from a chair” [21]. Patients were then grouped based on their response and there were no patients identified with the first response, resulting in three groups (12 patients in group one who selected response [2], 12 patients in group two who selected response [3], and seven patients in group three who selected response [4]) [21]. Group three and group two patients descended stairs faster than group one patients, group three displayed greater involved and uninvolved mean peak isokinetic knee extensor

torque per BW than groups one and two, and group three patients displayed higher KOS-ADKLS scores than group one subjects [21]. Therefore, the stair descent times suggested that group two patients need less home-based PT to assist with stair climbing [21]. Additionally, a moderate inverse relationship between uninvolved and involved mean peak isokinetic knee extensor torque per BW and stair descent time was revealed [21]. These results support the association between quadriceps muscle group strength and the close relationship between quadriceps muscle group strength and the patients' ability to safely descend stairs during the initial three to four weeks post-TKA [21]. The authors concluded that the perception of chair-rise ability at three to four weeks post-TKA is useful in helping physical therapists to determine patient readiness to begin stair-climbing [21]. They concluded with the suggestion that each group may benefit most from different rehabilitation focuses [21].

Naal et al. also assessed patients' functional ability after total joint replacements by examining different self-reported questionnaires [19]. The validity of the UCLA activity scale, Activity Rating Scale (ARS), and Tegner score were evaluated through correlations to the International Physical Activity Questionnaire (IPAQ). Reliability, feasibility, and floor ceiling effects of each were also discussed in their article. It was concluded that the UCLA was able to discriminate between insufficiently and sufficiently active patients, as classified by IPAQ, in patients undergoing THA or TKA [19]. All three questionnaires also had high Cohen's kappa (k_w) reliability values for TKA patients [19]. The UCLA score also had the highest completion rate in patients undergoing TKA [19]. Based off of these findings, the authors concluded that the UCLA scale served as a reliable, valid, and feasible assessment tool for activity levels in patients undergoing total joint replacements [19].

Conclusion

Knee extensor strength has been reported to remain significantly less than healthy controls after surgery, which has led to compensatory motions and functional deficits [15, 19, 23, 25]. Although multiple authors have discussed the importance of rehabilitation focused on quadriceps strengthening, the rehabilitative programs discussed in the literature did not bring back healthy strength levels and proper function in the knee joint post-TKA [18, 21, 25, 26]. Additionally, knee range of motion and activities of daily living were also not fully restored [18,

26, 29]. Therefore, without the restoration of proper function and strength to the knee joint, compensatory motion continued to occur during gait [18].

Knee Flexor Moments and the Development of Compensatory Motions

Introduction

The action of a healthy knee primarily occurred in the sagittal plane to produce flexion and extension during walking. As explained by previous studies, the cause of this motion relied on forces from the knee flexor and extensor muscle groups, which produced external knee extension and flexion moments, respectively [2]. Knee rotation occurred around multiple axes of rotation during flexion and extension causing the moment arm length to change throughout this motion [11], a feature that implant manufacturers have replicated. When the moment arm is increased, less extensor force is required for extension, which ultimately decreases the knee flexor moment [2, 8, 10]. Despite the attempt from TKA implant companies to replicate the normal knee, studies have revealed that forces, moments, and overall step cycle of TKA knees are not restored to healthy values, leading to compensatory motions with functional activities [17, 24, 26]. Patients with a small peak flexion moment at post-TKA also presented with anterior knee pain (AKP) [24].

Review of Literature

Costigan et al. investigated knee dynamics in normal volunteers during stair climbing and level walking to evaluate estimates of the net knee forces and moments [2]. Thirty-five university students, averaging 24.6 years old, without previous history of lower limb pain were included [2]. They walked in their own shoes at a natural, self-selected pace [2]. Stepping cycle used includes the swing phase, toe-off of test foot, stance phase, and contact with force plate until subsequent toe-off from force plate. Knee angles were computed by the floating axis technique with forces and moments about the three principle axes for the shank: the posterior-anterior line of progression, lateral-medial condyles of the femur, and distal-proximal long axis of the limb [2]. Forces and moments were computed by the inverse dynamic approach and were normalized by body weight and presented as 100% of the gait cycle [2]. Estimated contact forces of the tibia based on subject-specific knee models were estimated by the amount of quad and hamstring muscle forces [2]. All the loading occurred during the stance phase in level

walking, while stair ascent had maximum load occurring at 60° of knee flexion which at this point has a smaller joint contact area [2]. Within the first 20% of the stance phase, the external knee moment increased to 1.0 Nm/kg, but then dropped to 0.0 Nm/kg through 20% - 40% of the stance, indicating that the knee extensor muscles were increasingly active in the first phase of stance [2]. During flat land walking, the knee was not flexed more than 20°, but reached 60° with stair ascending resulting in the largest moment to occur [2]. The net knee forces were not different between level walking and stair ascent [2]. Patellar force resulted from an increase in the pull of the quadriceps being activated, which increased tension in the patellar tendon and tended to pull the tibia forward and up [2]. The patellar force was three times the amount of body weight on average for 45% of the gait cycle when knee flexion angle was over 60° [2].

Iwaki et al. investigated the multiple planes and angles of the tibiofemoral joint during flexion and extension [11]. This study also examined non surgical knees, as seen in the study by Costigan et al. [2]. Two cadaveric knees were imaged and dissected in males from 25 to 55 years old. MRI images were taken throughout flexion, extension, and longitudinal rotation to allow for relative positions and shapes of the medial and lateral compartments of bones and cartilage to be established separately throughout flexion [11]. Menisci and cruciate ligaments can be imaged with the capsule intact while the knee moves. The purpose of the imaging was to deduce how the tibia rotates and translates in relation to the fibula, which can be applied to the living knee [11]. The femur was positioned in full external rotation at 90° and internally rotated at 45°, 90°, 110°, and 120° manually with a force comparable to that applied in full extension [11]. Important landmarks to note were anterior and posterior circular surface on the femoral condyles, angular arcs of the femoral circle both medial and lateral, and extension (posterior) and flexion (anterior) facets [11]. The MRI revealed that arcs of the extension and flexion facet of the medial femoral condyle do not share a tangent point of junction. The medial tibial condyle makes contact with only the posterior portion of the posterior horn of the meniscus, while the anterior portion had an extension facet slope inferiorly to receive the anterior horn of the medial meniscus in extension [11]. The lateral tibial condyle also sloped inferiorly to accommodate the anterior horn of the lateral meniscus in the same position [11]. The lateral femoral condyle revealed that the lateral articular surface was actually 6 mm shorter than the medial, and the femur in full flexion was only in contact with the posterior horn [11]. In extension, the anterior horn is more prominent laterally [11]. Flexion measurements were recorded separately on the

medial and lateral side. From 10° to full extension, the femoral extension facet was about 8 mm anterior to the arc ranging from 30° to 120° of flexion [11]. In between, the center of rotation from 30° to 10° transferred from the femoral flexion facet to the extension facet without anteroposterior motion of the condyle [11].

Rotation of the femur occurred around the extension facet center, and tibiofemoral motion was pure sliding [11]. Femoral flexion facets were in contact with the tibial flexion facet from 30° to 120° with the femoral flexion facet center (FFC) above the contact area [11]. The lateral portion showed femoral contact with the tibia and posterior horn from 120°-110°, but FFC moved anteriorly 19 mm relative to the tibia if flexion was greater [11]. There was 15 mm of displacement between 120° to 45°, and 4 mm from 45° to -5° [11]. Flexion was accompanied by 20° of tibial internal rotation between 5° and -5° of flexion. These rotations occur if there is allowance for the displacement of FFC due to femoral rotation around extension facet center [11]. The distance between the contact point between the tibia and femur to the facet center changes depending on the flexion angle of the joint [11]. There is also a change of the contact location in both tibial and femoral points, and amount of translation depending on the angle [11]. This may help influence a proper design of prosthesis to allow for constant changes, and an understanding of what direction and amount of force was needed in order for muscles to pull the joint into flexion and extension [11]. The authors also expressed that research on living specimens is needed and the cadavers were under 60 years old, which could influence resulting data [11].

In a study by Insall et al., 118 posterior stabilized implants were followed up minimally two years and maximally four years post-TKA examining activity questionnaires and functional ability [10]. Similar to previous literature, the following were improved for all patients who received the posterior stabilized implants: the Hospital for Special Surgery knee-rating scale score, the ability to walk an unlimited distance and to climb up and down stairs without support, and range of motion [10, 26]. The authors suggested that the moment arm seen in the patella and quadriceps mechanism is longer in the posterior stabilized implants because the contact points between femoral and tibial components have a more posterior location than the corresponding contact points compared to the original total condylar design [10]. Since the patellar tendon force and resulting moment is responsible for knee extension, then the change to a posterior stabilized condylar implant should result in an increased moment arm [10]. Therefore, a lower

quadriceps force should be required for identical extension moment [10]. The authors concluded that the longer moment arm of these mechanisms contributed to the improvement in the posterior stabilized implant data.

Rather than a posterior stabilized model as seen in Insall et al., Heyse et al. examined how the amount of quadriceps force required for knee extension changed based on the presence of the cruciate ligaments [8, 10]. The authors hypothesize that a posterior-stabilized implant with a better reproducible roll back would eventually lead to lower quadriceps forces due to a tibial insertion being relatively translated anteriorly. Low extension moment was considered to be biomechanically advantageous because it delivers a better degree of efficacy of muscle torque [8]. Full knee extension that requires an increase in quad force may lead to early fatigue, leading to strain and other deficiencies that may lead to pain [8]. Eight fresh frozen human knee specimens, seven male and one female, with stable ligaments were mounted in a knee stimulator designed to allow isokinetic flexion-extension motions [8]. Both were measured in cruciate retaining and PCL resected set ups. Quadriceps forces increased significantly for resected PCL in both designs, but decreased with posterior stabilizing implants to its initial levels with PCL intact [8]. The lowest quadriceps forces for the posterior stabilizing design compared to the others were found in mid-flexion from 60° to 70° with no significant differences in full extension and flexion [8].

The authors discussed that the PCL's purpose is to deliver anterior-posterior stability by limiting strains that push the tibia posteriorly, accounting for why there was less quad force required with the ligament intact. Therefore based off the principle of moments forces, a posteriorly shifted tibia led to increased quadriceps forces [8]. This principle states that forces decreased with a growing distance between rotational axis and extensor mechanism [8]. The authors also discussed that the longitudinal rotational axis lies anterior to the flexion-extension axis and passes the insertion of the ACL and PCL's origin [8]. The physiological movement of the knee consisted of more posterior motion of the lateral condyle at an internal rotation of the tibia with respect to the femur with increasing knee flexion. A more ventral position of the tibia, relative to the femur is therefore indicated with a posterior stabilized design. The authors conclude that mean forces beyond 70° of flexion may be significantly lower in a posterior stabilized design in comparison to the four other groups, therefore they advise to use this type of implant [8].

The effects of chair rise and joint biomechanics have also been examined in OA and TKA patients, as observed by Su et al. [26]. The authors observed the biomechanics of the hip, knee, and ankle joints and compensatory mechanisms of chair-rise between patients at two to six years post-TKA, mild OA without TKA, and healthy elderly patients [26]. As seen in Costigan et al., the forces and moments required to produce motion were calculated by inverse dynamics [2, 26]. Each patient rose from a height adjustable chair corresponding to 115%, 100%, 80%, 65% of their knee height at preferred speed without armrest usage [26]. Results revealed that the duration for rising from a chair increased in OA and TKA groups as chair height decreased [26]. More forward displacement of their center of mass and slower extension speed was displayed by the two groups compared to the healthy control patients, but decreased chair height increased the extension speed differences among all three groups [26]. In addition to maximal hip flexion angle, the largest maximal flexion angle of the knee for all groups also occurred at 65% of knee height during the end of the forward leaning phase [26]. The maximum flexion moments of hip, knee, and ankle dorsiflexion occurred at the beginning of extension [26]. Specifically in the TKA patients, the involved side had a higher maximum hip flexion moment than the healthy control, while the maximal knee flexion moment for TKA and OA groups were lower than the healthy control, especially at 65% and 80% chair height [26]. At the ankle, the involved side of the TKA group had the highest dorsiflexion moment, and the OA patients revealed the lowest values [26].

Due to the decreased knee flexion and increased hip flexion, the authors concluded that both TKA and OA patients tended to lean forward more and shift their center of mass to the involved side during the rising maneuver [26]. This maneuver brought the center of mass above the knee and anterior to the hip and ankle, instead of directly above the hip and ankle, as seen in the healthy control group. The authors concluded that this compensatory motion will decrease the flexion angle, reaction force, and flexion moment of the involved knee where quadriceps strength may be weaker than normal [26]. Therefore, post-TKA may demonstrate better results than mild OA for rising mechanisms, as these findings were similar to the healthy control at 100% and 115% of knee height [26].

Smith et al. examined (1) if abnormal external flexion and extension moment patterns at the knee were present post-TKA and identifiable pre-surgery and (2) if higher external flexion moment at the knee is a predictive factor for the presence or severity of post-TKA anterior knee

pain (AKP) [24]. Thirty-four OA patients with 41 TKAs were tested and compared to 20 control participants [24]. Assessments measured clinical knee scoring and gait analysis at two time points: pre-TKA and 12-18 months post-TKA [24]. The *Profix* total knee system (Smith and Nephew Richards Inc., Memphis, TN) was used with a medial parapatellar or subvastus approach [24]. Clinical evaluation included a knee society clinical rating system, knee pain scale, and knee pain diagram to determine AKP [24]. Rather than having patients complete chair rising [26], gait was recorded by Vicon 370 motion analysis system via six 50 Hz cameras, and GRF was measured by two AMTI force plates at 2000 Hz [24]. All trials were completed at a naturally selected walking speed in comfortable habitual footwear with a low heel, and external knee joint moments were calculated from kinematic data in Vicon Clinical Manager using standard inverse dynamics and anthropometric values [24]. Society Score (KSS) and TKA knee society function score increased significantly from pre to post, and Knee pain scale decreased significantly pre to post-TKA [24]. Anterior Knee Pain was present in almost half of the participants at the 12-18 months follow up in equal proportions of patellar resurfacing and no resurfacing group [24]. Six out of 21 patients who reported AKP at pre-TKA developed this pain post-TKA [24]. Self-selected walking speeds significantly increased [24]. All temporal spatial parameters also significantly improved post-TKA, whereas the control subjects showed similar values to post-TKA patients except that controls had significantly greater limb support, double limb support, and lower stance phase times [24]. Wave forms also presented findings that there were no significant differences of mid-stance knee flexion moment from pre to post-TKA, but knees with AKP post-TKA had similar pre and post peak mid-stance flexion moments,[24]. Knees that developed post-TKA AKP had a significantly higher pre-TKA peak mean flexion moment compared to the pre-TKA values of those without anterior knee pain, but decreased post-TKA [24]. Pre-TKA peak flexion moment was determined as the best predictor for the presence of AKP to occur post-TKA from PC and univariate logistic regression models [24]. The authors suggested that the frequency and severity of AKP may be explained by the increased internal extension moment, which is generated by the knee extensor muscle group, resulting in external flexion moments that contribute to greater forces on the patellofemoral joint during early mid-stance [24].

A study by McClelland et al. investigated the prevalence of abnormal knee flexion-extension patterns during stair ascent and descent for TKA patients [17]. TKA participants

included individuals who were post-TKA, for the treatment of OA, at 12 - 18 months and were able to walk 10 m without assistance [17]. All 40 TKA participants received fully cemented Genesis II posterior stabilized prosthesis, and were compared to 40 healthy control participants. Participants walked down a 10 m walkway with two force plates on the floor, and one force plate on the first step of the staircase. The beginning of the step cycle is represented at 0% while toe-off is signified at the end of the step cycle at 100% [17]. Participants were instructed to take two steps on the level walkway before ascending [17]. Unlike the previous stair studies, no handrails were present for support and data collection stopped if they were unable to complete the task properly [17].

Out of the controls in the study by McClelland et al., 83% of TKA participants were able to ascend and descend stairs independently, while only 65% and 53% of TKA patients were able to complete the stair ascent and descent trials, respectively [17]. TKA patients and controls' knee motion step cycle pattern were separated into (1) normal and (2) abnormal significantly different clusters [17]. All control and 77% of participants were classified in Cluster 1 due to their normal knee moment and step cycle pattern, and the remaining TKA participants were categorized in Cluster 2 due to their abnormal knee pattern [17]. Peak knee flexion moment was significantly reduced, and the change of moment direction from flexion to extension occurred earlier in the step cycle of Cluster 2 during stair ascent [17]. The change of knee extension to flexion moment in Cluster 2 was characterized by a delay, and the flexion moment in early stance was absent during stair descent [17]. The authors discussed that the reduction of knee flexion moment and premature change to knee extension indicated avoidance of generating a knee flexion moment [17]. This avoidance was explained to serve as a compensatory reaction to instability of specific implant designs [17]. Peak knee flexion angles and moments, however, were not significantly different between unilateral and bilateral TKA values [17]. It is also important to note that TKA participants who was able to ascend and descend had a similar pattern to the control group, but the proportion of participants who demonstrated an abnormal moment pattern was too small to allow meaningful statistical data [17].

Similarly to Costigan et al., Vallabhajousla et al. discussed how the use of stairs increases kinetic variables at the knee. The authors investigated stability through power expended and external adductor moments at the hip, knee, and ankle joint during stair ascent initiated by a walk compared to initiated from standing [27]. Additionally, the authors examined if this was present

only at the first step or also at the next ipsilateral step [27]. Ten healthy subjects were randomly assigned to approach the stairs from a standing position or to walk 5 m at a comfortable speed in sport shoes [27]. The participants showed significantly greater peak abductor moments at the knee and hip when initiating stairs ascent from a walk [27]. Additionally, significantly greater peak ankle (20%), knee (20%), and hip abductor moments (20%) occurred at the second ipsilateral step [27]. Significantly greater peak values of power were also revealed at the ankle (48%), knee (43%), and hip (42%) at the second ipsilateral step [27]. Peak power was also significantly greater absorbed at the ankle (44%), knee (50%), and hip (64%) at the second ipsilateral step [27]. The authors concluded in their discussion that greater peak hip abductor moments with initiating stair ascent with walking may indicate increased activity of ipsilateral hip abductors [27]. This may be assisting with contralateral limb to avoid contact with stepping by counteracting pelvic drop on the contralateral side [27]. It is also possible that initiating stair ascent from a walk could have resulted in greater velocity, resulting in greater peak joint moments at the knee and hip [27]. The authors conclude by suggesting that using stair ascent reveals greater peak moment and powers while ascending the second ipsilateral step, to highlight the greater effort required for stability in the frontal plane, and the contralateral strength for clearing the intermediate step [27].

Another article by Vallabhajosula et al. examined how starting from afar compared to starting statically directly in front of a stair case will alter joint moments and powers [28]. The authors not only predicted that joint moments and powers during stair negotiation will be different in these two conditions, but these differences will also appear in consecutive ipsilateral footfalls on the stairs [28]. Kinematic data was collected from ten healthy young adults with eight cameras at 60 Hz, and two platforms at 600 Hz in the first and third stair tread. Dimensions of the staircase (18 cm step rise, 46 cm step width, 28 cm step tread, and angle of 32.73°) were selected because it is frequently encountered and within recommended stair dimensions by the Occupational Safety and Health Standards [28]. Trials were not used if the use of handrails or loss of balance occurred. Five trials for both randomized separate conditions were averaged for starting farther away from the stairs and starting in front of the stairs [28]. Participants were instructed to walk towards the stairs from a distance of 5 m within 10% of their pre-determined self-selected speed [28]. Findings showed that initial speed had minimal effect on the ankle joint moments, and peak positive ankle power starting from farther away was of

lesser value compared to starting in front of the stairs before toe off [28]. Peak knee extensor and hip extensor moment following foot strike was 10% greater when participants ascended from farther away, and decreased at the second step by 21% [28]. Peak knee flexor joint moment was also significantly greater in the first step by 62% [28]. Participants produced 8% more positive power on the second step when starting farther away, but 2% less power on the second step when starting in front of the staircase [28]. Knee power also decreased from first to second step by 15% [28]. The authors discussed that a possible reason for the differing values between the first and second step may be due to decreased velocity [28]. The authors also explain that at toe-off from first to third step in comparison to the toe off from second to final step, muscle activation changes due to less knee flexion required when reaching the final step [28].

Conclusion

Despite that stair ascent caused greater knee flexion moment in healthy individuals [10, 27, 28], moments for TKA patients have been shown to remain below healthy values [10, 17, 24]. There was also a greater difference reported between healthy and TKA patients during stair ascent when compared to level walking [2]. The reduced knee flexion moment of TKA patients indicated abnormal knee function and compensatory mechanism with functional activities, as explained by the principle of moments force [8, 17].

Single Radius Femoral Implant

Introduction

Historically, the multiradius (MR) femoral implant had been commonly used in TKA procedures because of its similar kinematic design to a healthy human knee. However, with the prevalence of AKP in TKA patients, combined with poor knee extensor strength and a decrease in knee range of motion, compensatory gait patterns became unavoidable [26]. Therefore, the single radius (SR) implant was introduced with a new and distinguishing characteristic of a fixed posterior center of rotation, which in theory lengthened the lever arm of the knee during knee extension [3, 7, 16]. Current literature has examined isokinetic strength and torque in both living and cadaveric populations to determine if increased lever arm would reduce quadriceps tension during extension [3, 6, 22]. Although long-term outcomes have yet to be published, clinical outcomes suggested AKP decreased and function increased in those who have received an SR implant compared to those who have received a MR implant [6, 7, 16, 30].

Review of Literature

In order to test the theory that SR required less force for extension, Ostermeier et al. performed a cadaveric study of SR and MR implants. The research team addressed that abnormal muscle function after TKA may occur for multiple reasons, such as loss of proprioception, muscle capacity, implant design, or alternations in lever arms and extension moments [22]. Stabilization of the flexion/extension axis movement is reduced and knee extensor lever arm is improved or restored to physiological levels, which may result in higher extension forces [22]. The purpose of this study is to investigate the amount of quadriceps force required to extend the knee during isokinetic extension pre and post -TKA in MR and SR implants, and hypothesizing that SR would restore to physiological levels [22]. The researchers strapped 12 specimens, averaging 68 years of age, to isokinetic flexion-extension stimulation. To replicate magnitudes close to physiological forces and moments about the knee, the tibia was moved by three separate hydraulic cylinders stimulating quadriceps muscle force, co-contraction hamstring force, and application of an external flexion moment [22]. Measurements were completed from 120° to full extension with a constant hamstring flexion force of 100 N and constant internal, external flexion moment of 31 Nm applied throughout [22]. The quadriceps cylinder was applied a constant extension moment at the swing arm to create 31 Nm for nominal extension moment, and the resultant quadriceps force to maintain this moment was recorded [22].

Results of the study by Ostermeier et al. revealed that significantly higher quadriceps force output for MR was necessary to generate the same extension moment as the SR [22]. The authors explained that the change of lever arm during extension of the knee, and contact point translation of the tibiofemoral and patellofemoral joint will alter the quadriceps force on the knee [22]. The extensor mechanism efficiency is also increased when more stability of the flexion/extension axis can be restored, to allow less required quadriceps force needed to create the same extension moment [22]. Additionally, maximum quadriceps load following MR occurred at lower flexion angles (90°) and the force remained higher when going into greater extension [22]. The authors concluded that the SR implant can restore physiological tibiofemoral movement, resulting in a more stable flexion/extension axis compared to MR implant, and therefore possible that the physiological lever arm could be restored [22].

Ward et al. also examined cadaveric knees with SR TKA implants [31]. The authors focused on determining a possible cause of the improved mechanical quad advantage. The authors investigated three options: 1) flexion moment about the tibiofemoral joint was due to the hanging mass, 2) patellar moment arm governed the transmission of force across the tibiofemoral joint to the patellar tendon, 3) the quad force – patellar tendon force ratio (QF: PTF) altered the transmission of force across the patella from the patellar tendon to the quad tendon [31]. There were six cadavers between the age of 60 to 80 years old that were set in knee extension with 3 kg load on the tibia, and compared to normal non-implant knees. Patellar tendon moment arm and the patellar tendon angle was observed through fluoroscope sagittal images, along with Vicon motion capture to measure relative movement and force between the femur, patella, and tibia [31]. Results showed that the hanging mass was not a contributor for the different flexion moment between TKA and normal groups due to the consistent hanging mass for all knees [31]. The patellar moment arm was also not a cause for the quad advantage, as 15% and 20% of quad force of TKA was greater than normal, yet the moment arm was less than 5% greater than normal in flexion range. The 3D images revealed that the SR moment arm was lower than normal throughout the flexion range [31]. Therefore, the authors concluded that alterations to quad force – patellar tendon force ratio contributed to reducing the quad force post-TKA by transmitting the force across the patella from the patellar tendon to the quad tendon [31]. The authors concluded with suggestion of future work focusing on improving the patellofemoral joint, rather than focusing on tibiofemoral joint [31].

D’Lima et al. also investigated the biomechanical differences between SR and MR implants on cadavers [3]. Commonly used femoral implants possessed a changing sagittal geometry with the center of rotation shifting from an anterior location to a posterior location, during flexion and extension, due to the changing radius of the curvature [3]. The authors explain that a recently the SR implant maintained one sagittal radius from hyperextension to flexion with the center of rotation located close to the transepicondylar axis [3]. This center of rotation is more posterior to comparable knee implants to increase the extensor moment arm [3]. The authors examined if the increase in extensor moment arm affects quadriceps tension [3].

The authors collected data on six fresh frozen knees from human cadavers in three different conditions in the following order: normal, Scorpio SR (SR implant Scorpio CR, Howmedica Osteonics), and Control MR implant (Series 7000, Howmedica Osteonics) [3].

Kinematic data was collected from two trials per knee, using a dynamic quadriceps driven closed kinetic chain knee stimulator (Oxford knee rig) and a 3D motion analysis using electromagnetic tracking device in simulated stair climbing settings [3]. Peak knee flexion moment at approximately 40 Nm was generated comparable with the reported moment during stair climbing after TKA [3]. Results revealed that there was less femoral rollback, more valgum in extension, and less rotation seen in implant conditions compared to normal [3]. Normal knees consistently generated higher quadriceps tension than either implant conditions, while the SR showed 5% to 20% reduction in quadriceps tension and lower patellar compressive forces relative to the control at flexion angles greater than 40° [3]. Quadriceps tension and patellar compressive forces were correlated with each other and directly correlated with knee flexion angles for all conditions [3]. The results supported that a longer lever arm reduced the tension of the quadriceps during knee extension at angles that typically generated high knee moments typically seen during stair climbing [3]. The reduction of patellar forces for the SR compared with control may positively impact patellar component hold and improve the knee extensor function [3]. In conjunction, there were relatively small kinematic differences between control and SR during kinetic chain knee extension at angles and loads tested [3]. This suggested that the changing center of rotation does not have any additional positive or negative affect on knee kinematics [3].

Hall et al. also compared the advantages of having a contemporary SR compared to a PCL retaining MR implant [7]. In this randomized study, 50 SR (Homedica Osteonics Scorpio, Stryker Orthopaedics Mahwah NJ) and 50 MR (Johnson & Johnson PFC; DePuy, Johnson & Johnson, Warsaw, Ind) were evaluated. All participants received three weeks of physical therapy post-TKA focusing on quadriceps strengthening, range of motion, and weight bearing transition. Range of motion for the Scorpio SR ranges from -15° to 75° knee flexion with fixed, posterior instant center of rotation as studied in D'Lima et al. [3], which theoretically, increases the SR moment compared to the MR design [7]. AROM and KSS were assessed by a physician at pre-TKA, four to six weeks, three month, and 1-year post-op [7]. The ability to rise independently from a 16 inch high chair was examined only post-TKA, which was than classified in either an assisted or unassisted chair-rise category. A student *t*-test for age, height, weight, range of motion, and KSS was conducted, along with Pearson X^2 for chair rise ability and anterior knee pain when rising[7]. An increase of 38%-88% were able to rise from a chair without assistance in the SR group and an increase from 46%-82% of the MR group compared at 4-6 wks and 1 yr

post-TKA [7]. There were no significant differences between groups at any time point [7]. Anterior knee pain decreased from 32% to 15% in the SR group and 28% to 11% in the MR group at 4-6 weeks and 1 year post-TKA without sig diff between groups at any time point [7]. Extension at 4-6 weeks post-TKA in the SR group was not clinically significant and resolved by one year post-op [7]. Results concluded that extension improvements were not clinically significant between implants and resolved by 1 year [7]. There were no significant differences between groups in extension. Overall there is an increase of being able to go from sit to stand without assistance though and there was a decrease in anterior knee pain with the presence of a TKA implant [7].

Jo et al. also concluded with no significant differences between implants in their study. Intra-operative stability and clinical outcomes were compared between groups. There were 50 SR (66.4 years old average, Scorpio CR Zimmer) and 50 MR patients (67.5 years old average, NexGen CR Zimmer) who followed up in this study at an average of 36.2 months post-TKA [12]. Range of motion, x-ray in full extension for joint line position, and clinical outcomes were examined in both groups. Clinical outcomes include passive range of motion, the Hospital for Special Surgery Score, the Western Ontario and McMaster Universities Osteoarthritis Index score, and a Visual Analogue Scale of AKP with stair climbing. Intra-operative mean total stability was only significantly better in SR than MR 30° of flexion [12]. The authors accounted the beneficial stability towards better ligament stability during mid-flexion based on maintained length of ligament from the fixed rotation. However, overall mean stability of both groups were noticeably low at 0° of flexion, and all clinical outcome scores were not significantly different [12]. Maximum knee joint flexion, additionally, were not significantly different between groups [12]. The authors concluded, as did Hall et al., that this design did not culminate in better functional outcomes [7, 12].

Similar results were seen in a study by Hinajeros et al., who examined functional results and the quality of life. Range of motion and the perceived ability to perform activities of daily living, such as stair ascent, descent, kneeling, and squatting, were also examined. Unlike Jo et al., this study examined posterior stabilized implants, where 285 received the MR Genutech Total Knee System and 295 received the SR Stryker Traithalon implant [9]. The TKA surgery was also completed by nine different surgeons, but there was no learning curve due to their experience. The KSS knee, KSS function, total KSS, VAS score for pain and SF-36 physical at

1 year and 5 years post-TKA were not significantly different between implants, but they all significantly improved compared to post-TKA [9]. Post-TKA expectation of achievement for ascending stairs, descending stairs, kneeling, squatting, and activities of daily living were also not significantly different between implants, post-TKA, but all significantly improved compared to post-TKA [9]. The authors concluded that their study failed to prove better functioning with SR at short term and medium term follow up [9]. Range of motion was also not significantly different throughout the study [9]. Since both implants actually improved in perceived function and ability, the authors suggested that the single radius of the femoral component should not be considered the main factor with choosing a TKA model [9].

Clinical scores, as well as quadriceps force and power, were also examine in a study by Kim et al. Similarly to Hinajeros et al., the authors examined the posterior stabilized SR implant (Stryker triathlon) and if it is advantageous for quad recovery [13]. The authors measured if the amount of patients with physiological levels of quad force and power, and American KSS would be higher in SR. Data was collected at pre-TKA and post-TKA at 6 weeks, three months, six months, and one year from 55 SR and 54 MR (PFC Sigma) patients [13]. Quad force and power at every time period were not significant between groups [13]. Mean quad force, in fact, at six months could reach pre-TKA levels, while mean quad power at three months post could reach pre-TKA levels in both implants [13]. Post-TKA clinical scores were also not significantly different. The authors suggested that the femoral design in a TKA would not influence quad function after surgery [13].

Mahoney et al. also studied the Scorpio SR implant, but compared it to 7000 PPSK MR prosthesis [16]. As described in D'Lima et al., the authors examined the kinematic theory that knee flexion and extension occurred around the around a center of rotation that moves anteriorly and proximal in extension and distal and posterior with flexion [3, 16]. The MR device closely followed this description in movement, but the authors discussed that a relatively posterior flexion-extension axis would lengthen extensor mechanism moment arms and therefore, improve extensor mechanism function [16]. This is due to the findings that MR device does not restore the lever arms to normal, with the greatest reduction occurring in the last 30° of extension [16]. Eighty-three MR and 101 SR participants, with an average age of 69 were examined. The participants answered three yes/no questions about no arm assisted sit to stand task and actually performed chair rising task as seen in Hall et al [7]. Questions and evaluations were given at six

weeks, three months, six months, one year, and two years post-TKA [3]. Knee Society Scores and functional questions improved post-TKA for both groups, but flexion significantly increased for only the SR group at six weeks [16]. On the other hand, SR showed no significant difference compared to MR at two years, 120° and 122°, respectively [16]. The SR group consisted of a higher percentage of participants rising from a chair independently at six weeks, one year, and two years compared to the MR, which the authors associated to a reduction of anterior knee pain [16]. SR group also had significantly less amount of anterior knee pain at 1 and 2 years postoperatively [16]. The authors associated these differences and lower anterior knee pain to improved extensor mechanisms with the SR implant [16].

Similar to the previous studies, Gomez-Barrena et al. examined the extensor performance outcomes of Scorpio SR, but compared it to the NexGen MR implant by using the knee scoring system, recording the number of physiotherapy sessions completed, and the number of post-TKA weeks until the use of one crutch was implemented [6]. Isokinetic evaluation for flexion and extension with a 40 Hz dynamometer balance platform, and a gait cycle evaluation of the velocity throughout each gait phase was also used [6]. These assessments were performed at an average of 10.9 months and 10.7 months post-TKA for the 30 patients in the MR control group and the 30 patients in the SR evaluation group, respectively [6]. Comparative statistical analysis for quantitative variables was assessed by Student's *t*-test after assessing normal distribution by the Kolmogorov-Smirnov test. Clinical Knee Scoring System did not expose any difference between groups, but the SR participants completed fewer physiotherapy sessions and faster time to one crutch usage [6]. Comparative isokinetic analysis for peak extension torque was significantly higher for the SR group only, while peak flexion torque was significantly higher for the MR group only [6]. Stability assessment revealed that SR had a higher surface/length ratio, suggesting that the body's center of gravity oscillation decreased compared to MR [6]. Gait cycle evaluation revealed a faster contralateral swing phase speed for the SR group, which may indicate that the leg with the prosthesis provided a more solid support to allow faster swing movement [6]. The authors explained that better quadriceps recovery may be responsible for increased isokinetic peak extension and faster contralateral swing phase in SR patients, but that more research is needed to determine quadriceps weakness post TKA [6].

Scorpio was also compared to Journey Bi-Cruciate Stabilized, another MR implant, in a retrospective comparative study by Digennaro et al. examining kinematic and kinetic differences

and its influence on clinical outcomes [5]. Digennaro et al. also described the Scorpio NRG SR implant knee system has an axial, unconstrained, fixed-bearing design that allows the femur to rotate freely about the tibia in the transverse plane but limits anterior-posterior translation of the femur in knee flexion [5]. The asymmetric shape of the condyles of the Journey BCS more closely reproduces the motion of normal knees by its changing the radius and femoral component that consistently rolls back after engaging the cam and post at 54° of flexion and offers a medial pivot [5]. There were 297 TKA implants in 281 subjects examined with follow-up observations at 12-50 months post operatively, but 15 SR and 16 MS knees were additionally examined by fluoroscope at six months postoperatively [5]. Fluoroscopy measurements were completed with stair climbing, chair rising/sitting, and step up/down with a standard fluoroscope [5]. Three 21-cm high steps were used for stair climbing and step-ups, while only the first step's data was recorded. Chair height for sitting was set at a height to allow for knee flexion of 80° [5].

Both implants in the study by Digennaro et al. showed posterior translation in all activities and progressive internal rotation of the femur, relative to the tibia, with knee flexion [5]. KOOS subcategories of pain and Quality of Living (QOL) was significantly greater in the MR group compared to SR[5]. In all three motor tasks, medial and lateral CP displacements in the SR group were generally located posteriorly throughout the flexion arc; the MR group showed a coupled posterior translation of the two CPs between 0° and 30° knee flexion, similar to Iwaki et al., and higher posterior translation of the lateral than the medial CP for knee flexion greater than 50° [5, 11]. Contact line was greater in the MR group for all three actions, while rollback occurred at small flexion angles in this group, unlike in SR [5]. Unlike the previous literature mentioned, the MR design can result in rollback and screw home mechanism, while the SR group demonstrated consistent axial rotation with a central pivot and good posterior positioning of the femoral component of the tibial plate. On the other hand, stiffness was exhibited in the MR group which may affect ROM, posterior femoral rotation, patellofemoral kinematics and posterior condyle offsets. Effects to these variables may lead to soft tissue mechanical stress [5].

Wang et al. examined the same theory described in Hall et al., that less quadriceps muscle force is required to produce knee flexion moment (40 N/m specifically) in the SR group than MR due to the length of the device's moment arm [7, 30]. The MR design was investigated as a possible cause of temporary varus-valgus knee instability while shifting from longer to shorter

radii lengths during knee flexion [30]. Sixteen patients (eight SR, eight MR) were examined approximately 18 months post unilateral TKA to determine if compensatory adaptations, extensor activation, and knee stability differences existed while performing STS between groups [30]. Measurements were completed with an EMG, three high-speed video cameras, and an isokinetic dynamometer [30]. The STS task completed by the researchers required participants to stand up as quickly as possible and to remain standing for five seconds [30]. Isometric strength test for extension at 60° and flexion at 30° with EMG was completed [30]. Whole movement variables were divided into two distinct phases: the forward-thrust phase and flexion and extension phase for knee, hip, and shank [30]. The MR group had a greater STS time, greater trunk flexion angle, and the tendency of greater trunk flexion velocity [30]. In addition, the SR group compared to MR presented with a maximum trunk flexion angle that was 10° less during forward-thrust phase, 7°/s less trunk flexion velocity, and knee and hip extension velocity was 13.8°/s and 19.5°/s faster, respectively. The SR limb also had less adduction displacement than the MR limbs [30]. The authors explained the possibility the influence of knee extensor strength on these variables, indicating compensation, where even with kinematic adaptations for reducing knee extension, a greater knee extensor activation was still required [30]. The quadriceps muscles of the MR limb were significantly greater than the SR limb during the extension phase. Hamstring muscles also had greater co-activation (EMG) than SR during extension. This may have been influenced by the shorter MR quadriceps moment arm limb to accomplish rising from a chair as fast as possible [30]. They conclude that the SR design may generate the proper knee extensor moment with less quadriceps effort and maintain a stable knee joint while requiring less co-activation effort during the STS movement [30].

Unlike the other SR studies, Borrione et al. performed a retrospective five-year follow up of clinical and radiologic outcomes of only SR Scorpio TKA. The authors used 831 patients, 723 who were diagnosed with primary osteoarthritis [1]. Out of the 831, 505 patients were still alive who had not required surgical revision, with 80% PS design and 20% cruciate retaining [1]. All procedures were performed by one of the authors using an anteromedial parapatellar approach in 793 knees, and lateral approach in 38 knees [1]. KSS for pain, range of motion, and stability and function was distributed. Radiographic evaluation based on anterior-posterior view of knee while standing, lateral view at 30° of flexion, merchant view, and long leg view [1]. Survivorship analysis according to actuarial method was conducted using revision for any reason

and revision for mechanical reason at the time of follow-up as the end-points [1]. Four knees had patellar complications: patellar fracture, patellar implant loosening that required revision, one extensor mechanism rupture, and one patellar instability [1]. Eight knees resulted with mechanical failures: isolated tibial component loosening in two, isolated patellar component loosening in one, both femoral and tibial components in three, pain from oversized tibial component, and painful stiffness in one knee [1]. There was low failure rate mechanically in the patella, while clinical KSS improved significantly [1]. The KSS functional component also significantly improved. Radiographically, there was a decrease in knee varum seen post-TKA (n = 125) and valgum (n = 26) in the frontal plane [1]. Mean active flexion significantly increased (from 107°, range 45° - 140°, pre-TKA to 114°, range of 70° - 140°) [1]. Complete extension was obtained in 524 knees (87%) at the last follow-up. 0.7% patellar-related complications [1]. The authors concluded that the clinical results were favorable and mechanical failure rate was low [1]. This cohort is still being followed to examine long-term clinical and radiological results [1].

Conclusion

Despite the biomechanical theory that less quadriceps force was required to complete the flexion and extension motion with a fixated, posterior center of rotation, previous literature is limited and has not reached a consensus on the effects of SR implants. Less quadriceps force was found to be required for knee extension in SR cadaveric studies, but these results may be limited with explanations in explaining walking or activities of daily living [3, 7, 22, 31]. In patients who have received an SR implant, low mechanical failure rate and favorable clinical results, such full extension, has been reported up to 6-year post-TKA [1]. Additionally, improved functional data, such as the ability to rise from a chair returned to healthy levels by one-year post-TKA [16, 30]. Although it was reported that compensatory motion of increased trunk flexion was visible among MR patients [16, 30], SR strength studies had conflicting results of quadriceps strength and power testing between implants [6, 13]. Additionally, not all studies have found clinical questionnaire and range of motion to be significantly different between implants [7, 9, 12]. These results have led to the suggestion for more studies on the SR implant examining kinetic variables post-TKA [6]

APPENDIX A. RESEARCH SUBJECT INFORMATION AND CONSENT FORM

TITLE: Biomechanical Comparison of Multi- and Single Radius Implant Designs During Level Walking and Stair Climbing Tasks

PROTOCOL NO.: 2014-018
WIRB® Protocol #20141194

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This consent form may contain words that you do not understand. Please ask the study doctor or the study staff to explain any words or information that you do not clearly understand. You may take home an unsigned copy of this consent form to think about or discuss with family or friends before making your decision.

SUMMARY

You are being asked to be in a research study. The purpose of this consent form is to help you decide if you want to be in the research study. Please read this consent form carefully. To be in a research study you must give your informed consent. “Informed consent” includes:

- Reading this consent form
- Having the study doctor or study staff explain the research study to you
- Asking questions about anything that is not clear, and

- Taking home an unsigned copy of this consent form. This gives you time to think about it and to talk to family or friends before you make your decision.

You should not join this research study until all of your questions are answered.

Things to know before deciding to take part in a research study:

- The main goal of a research study is to learn things to help patients in the future.
- The main goal of regular medical care is to help each patient.
- No one can promise that a research study will help you.
- Taking part in a research study is entirely voluntary. No one can make you take part.
- If you decide to take part, you can change your mind later on and withdraw from the research study.
- The decision to join or not join the research study will not cause you to lose any medical benefits. If you decide not to take part in this study, your doctor will continue to treat you.
- Parts of this study may involve standard medical care. Standard care is the treatment normally given for a certain condition or illness.
- After reading the consent form and having a discussion with the research staff, you should know which parts of the study are experimental (investigational) and which are standard medical care.
- Your medical records may become part of the research record. If that happens, your medical records may be looked at and/or copied by the sponsor of this study and government agencies or other groups associated with the study.

After reading and discussing the information in this consent form you should know:

- Why this research study is being done;
- What will happen during the research;
- Any possible benefits to you;
- The possible risks to you;
- How problems will be treated during the study and after the study is over.

If you take part in this research study, you will be given a copy of this signed and dated consent form.

PURPOSE OF THE STUDY

The purpose of this study is to compare the function of patients, implanted with either a multi-radii or a single radius total knee arthroplasty design, during level walking and stair climbing tasks. You are being asked to participate in this study because you are undergoing total knee arthroplasty. About 100 subjects are expected to participate.

PROCEDURES

If you decide to participate in this study, you will be randomly assigned (by chance) to one of four possible groups and receive either a single radius knee implant or one of three multiple radii

knee implants. You have an equal chance of being assigned to any one of the four implant groups. The implants that will be used in this study are:

- GetAroundKnee™, Stryker Orthopedics (single radius)
- Balanced Knee® System, Ortho Development (multiple radii),
- Persona™ Total Knee, Zimmer (multiple radii)
- NexGen®, Zimmer (multiple radii)

These types of implants are approved by the FDA for the type of surgery you are having and will be used according to their approved indication.

You will be asked to report to the University of Hawaii at Manoa, Kinesiology and Rehabilitation Science Laboratory (Gait Lab) (Sherriff 100) for all testing visits before and after your knee surgery.

Upon arrival to the Gait Lab, you will be asked to fill out one survey in reference to your current pain and activity level. Measurements about your body will be taken and you will be asked to perform the following tasks:

- (1) walk for 6 meters at a comfortable speed 6-10 times (Gait Analysis),
- (2) walking up and down stairs at a comfortable speed 3-4 times, and
- (3) push into stationary objects (fixed dynamometer) with your leg for three seconds for two different leg movements (Isometric Strength).

You will also be asked some questions about your daily activities. The entire visit will take approximately 60 minutes.

You will be asked to go to the Gait Lab for your first study visit before your surgery. You will be asked to return to the Gait Lab 5 more times over the next two years to repeat the procedures listed above (please see Table 1 below for visit schedule). Each visit to the Gait lab will take approximately 60 minutes.

Table 1. Visit Time Line

	Before Surgery	6 Weeks After Surgery	3 Months After Surgery	6 Months After Surgery	1 Year After Surgery	2 Years After Surgery
Gait Analysis (test)	X	X	X	X	X	X
Isometric Strength	X	X	X	X	X	X
Paper/Pencil Survey	X	X	X	X	X	X

RISKS AND DISCOMFORTS

Being randomized to one type of knee implant instead of the others, may lead to greater or lesser stability of the knee post-surgery.

There are risks associated with your knee replacement surgery, whether or not you participate in this study. These include:

- Blood clots that can, in rare cases, be life threatening
- Complications after a blood transfusion
- Allergic reaction to the medications or materials used
- Infection
- Injury to arteries or nerves in your leg
- Surgery may not reduce your pain and stiffness, possibly requiring more treatment
- Surgery may cause more pain
- Risks of anesthesia

You will be asked to review and sign a separate consent form for your knee surgery, and your surgeon will explain the risks of the procedure in more detail.

Gait analysis risks

Due to the level of physical activity involved during the testing procedures, there is a risk of injury. You may have pain in your affected joint during testing. You may also have some discomfort, muscle cramping or soreness during or after test sessions. Although we have people to assist you and handrails in place, there is a chance of falling during the test. There is a very remote chance of cardiac arrest and/or death. These risks are comparable to your routine rehabilitation and activities of daily living, and will not affect your recovery from the surgery.

You cannot participate in this study if you are pregnant because the information collected during the walking test may not accurately represent your normal walking characteristics. If you are unaware that you are pregnant, participation in this study will result in no more danger to the mother or fetus than normal activities of daily living. However, if you become pregnant or think you might be pregnant during the course of this study, you must inform the researchers, and you will be removed from study participation.

NEW INFORMATION

You will be told about anything new that might change your decision to be in this study. You may be asked to sign a revised consent form if this occurs.

BENEFITS

You may not receive direct/immediate benefits from study participation. However, you will obtain information regarding your walking gait, functional activity capacity, hip muscular strength, and behavioral characteristics. Results of this study may assist physicians, physical therapists, and athletic trainers to ensure the optimal clinical outcomes to maintain the beneficial effects of total knee replacement.

PAYMENT FOR PARTICIPATION

You will not be paid for your participation in the study.

You will be given \$5 that can be applied towards parking and/or transportation to the University of Hawaii Gait Laboratory each time you come for a visit. The money will be given to you after you arrive at the facility with a receipt, so it is a reimbursement. You will be reimbursed only for the visits that you attend.

COSTS

You are not expected to have additional costs related to the procedures and visits that may result from your participation in this research study.

Any additional costs associated with parking/transportation over and above the \$5 provided will be your responsibility. The fee for parking at the University of Hawaii parking structure is \$5 during the week and \$6 on the weekends.

ALTERNATIVE TREATMENT

If you decide not to participate in this study, you will receive your knee replacement surgery with the type of implant that your doctor feels is best for you. Your follow-up care will be the same whether or not you are in this study.

USE AND DISCLOSURE OF YOUR HEALTH INFORMATION:

By signing this form you are authorizing the use and disclosure of individually identifiable information. Your information will only be used/disclosed as described in this consent form and as permitted by state and federal laws. If you refuse to give permission, you will not be able to be in this research.

This consent covers all information about you that is used or collected for this study. It includes

- Past and present medical records
- Research records
- Records about your study visits.
- Information gathered for this research about:
 - Physical exams
 - Laboratory, x-ray, and other test results
 - Questionnaires
- Records about the implanted medical device.

Your authorization to use your identifiable health information will not expire even if you terminate your participation in this study or you are removed from this study by the study doctor. However, you may revoke your authorization to use your identifiable information at any time by submitting a written notification to the principal investigator, Cass Nakasone, MD at 888 S. King Street, Honolulu, HI 96813. If you decide to revoke (withdraw or “take back”) your authorization, your identifiable health information collected or created for this study shall not be used or disclosed by the study doctor after the date of receipt of the written revocation except to the extent that the law allows us to continue using your information. The investigators in this study are not required to destroy or retrieve any of your health information that was created, used or disclosed for this study prior to receiving your written revocation.

By signing this consent form you authorize the following parties to use and or disclose your identifiable health information collected or created for this study:

- Cass Nakasone, MD and his research staff for the purposes of conducting this research study.
- Straub Clinic & Hospital and Hawai'i Pacific Health

Your medical records may contain information about AIDS or HIV infection, venereal disease, treatment for alcohol and/or drug abuse, or mental health or psychiatric services. By signing this consent form, you authorize access to this information if it is in the records used by members of the research team.

The individuals named above may disclose your medical records, this consent form and the information about you created by this study to:

- The sponsor of this study and their designees (if applicable)
- Federal, state and local agencies having oversight over this research, such as the Office for Human Research Protections in the U.S. Department of Health and Human Services, Food and Drug Administration, the National Institutes of Health, etc.
- The University of Hawai'i
- Hawaii Pacific Health (HPH) Officials, the Western Institutional Review Board, and the HPH Office of Compliance for purposes of overseeing the research study and making sure that your ethical rights are being protected.

Some of the persons or groups that receive your study information may not be required to comply with federal privacy regulations, and your information may lose its federal privacy protection and your information may be disclosed without your permission.

COMPENSATION FOR INJURY

In the event of any physical injury from the research, only immediate and essential medical treatment is available. First Aid/CPR and a referral to a medical emergency room will be provided. In the event of any emergency incidence outside the lab as a result of this research, contact your regular medical doctor and inform the study coordinator: Cris Stickley Ph.D., ATC, at 808-956-3798. You should understand that, if you are injured in the course of this research process, you or your medical insurance will be billed for the costs of treating your injuries.

VOLUNTARY PARTICIPATION AND WITHDRAWAL

Your participation in this study is voluntary. You may decide not to participate or you may leave the study at any time. Your decision will not result in any penalty or loss of benefits to which you are entitled.

Your participation in this study may be stopped at any time by the study doctor or the sponsor without your consent for any of the following reasons:

- it is in your best interest;
- you do not consent to continue in the study after being told of changes in the research that may affect you;

- you become pregnant;
- or for any other reason.

If you leave the study before the planned final visit, you may be asked by the study doctor to have some of the end of study procedures done.

SOURCE OF FUNDING FOR THE STUDY

This research study is sponsored by the University of Hawaii, Manoa.

QUESTIONS

Contact Cris Stickley Ph.D., ATC at 808-956-3798 or Dr. Cass Nakasone at 808-522-4232 for any of the following reasons:

- if you have any questions about this study or your part in it
- if you feel you have had a research-related injury or
- if you have questions, concerns or complaints about the research

If you have questions about your rights as a research subject or if you have questions, concerns, input, or complaints about the research, you may contact:

Western Institutional Review Board® (WIRB®)
1019 39th Avenue SE Suite 120
Puyallup, Washington 98374-2115
Telephone: 1-800-562-4789 or 360-252-2500
E-mail: Help@wirb.com.

WIRB is a group of people who perform independent review of research.

WIRB will not be able to answer some study-specific questions, such as questions about appointment times. However, you may contact WIRB if the research staff cannot be reached or if you wish to talk to someone other than the research staff.

Do not sign this consent form unless you have had a chance to ask questions and have gotten satisfactory answers.

If you agree to be in this study, you will receive a signed and dated copy of this consent form for your records.

CONSENT

I have read this consent form. All my questions about the study and my part in it have been answered. I freely consent to be in this research study.

I authorize the use and disclosure of my health information to the parties listed in the authorization section of this consent for the purposes described above.

By signing this consent form, I have not given up any of my legal rights.

Subject Name (printed)

CONSENT SIGNATURE:

Signature of Subject

Date

Signature of Person Conducting Informed Consent Discussion

Date

APPENDIX B. ACTIVITY ASSESSMENT SURVEY

Subject ID#: _____ Data Collection Period 0 1 2 3 4 5 6 7

Please circle the number that best describes current activity level.

1. Wholly inactive, dependent on others, and can not leave residence
2. Mostly inactive or restricted to minimum activities of daily living
3. Sometimes participates in mild activities, such as walking, limited housework and limited shopping
4. Regularly participates in mild activities
5. Sometimes participates in moderate activities such as swimming or could do unlimited housework or shopping
6. Regularly participates in moderate activities
7. Regularly participates in active events such as bicycling
8. Regularly participates in active events, such as golf or bowling
9. Sometimes participates in impact sports such as jogging, tennis, skiing, acrobatics, ballet, heavy labor or backpacking
10. Regularly participates in impact sports

Please circle the number that best answers the following question. "How does your knee affect your ability to rise form a chair?":

1. "Because of my knee I cannot rise from a chair."
2. "Because of my knee, I can only rise from a chair if I use my hands and arms to assist."
3. "I have pain when rising from the seated position, but it does not affect my ability to rise from the seated position."
4. "My knee does not affect my ability to rise from a chair."

Are you satisfied with your implant?

Yes

No

APPENDIX C. DATA COLLECTION FORMS

Manual Muscle Testing Data Collection

Subject ID#: _____ Data Collection Period 0 1 2 3 4 5 6 7

Patient's Operated leg: L / R Dominant Leg: L / R

Tester: _____

	Left Leg						Right Leg					
	Trial 1 Score (ft-lb _f)	Pain Score (HHD/Jt)	Trail 2 Score (ft-lb _f)	Pain Score (HHD/Jt)	Trial 3 Score (ft-lb _f)	Pain Score (HHD/Jt)	Trial 1 Score (ft-lb _f)	Pain Score (HHD/Jt)	Trial 2 Score (ft-lb _f)	Pain Score (HHD/Jt)	Trial 3 Score (ft-lb _f)	Pain Score (HHD/Jt)
Hip abduction		/		/		/		/		/		/
Knee extension		/		/		/		/		/		/

Anthropometric Data

Subject ID#: _____ Date _____

Age _____ Gender: F / M

Data Collection Period 0 1 2 3 4 5

Patient's Operated leg: L / R Dominant Leg: L / R

Date of Surgery _____

Weeks after Surgery _____

Vicon/Nexus Measurements

Weight (kg)	
Height (mm)	
Age (yrs)	
Left leg length (mm)	
Left knee width (mm)	
Left ankle width (mm)	
Right leg length (mm)	
Right knee width (mm)	
Right ankle width (mm)	

Data Collection Form

Subject ID#: _____

Data Collection Period 0 1 2 3 4 5

Patient's Operated leg: L / R

Dominant leg: L / R

Total Trials: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Walking Trials		
Trial	Which foot hit the plate	Walking Pace (s)
1	R / L	
2	R / L	
3	R / L	

Stair Ascent		
Trial	Which foot hit the plate	Walking Pace (s)
1	R / L	
2	R / L	
3	R / L	

Stair Decent		
Trial	Which foot hit the plate	Walking Pace (s)
1	R / L	
2	R / L	
3	R / L	

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