A BIOMECHANICAL ANALYSIS OF KINETIC AND KINEMATIC VARIABLES IN OSTEOARTHRITIC KNEES FOLLOWING TOTAL KNEE ARTHROPLASTY

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAIʻI AT MĀNOA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

KINESIOLOGY AND REHABILITATION SCIENCES

DECEMBER 2020

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LIST OF ABBREVIATIONS

Activity of Daily Living……ADL

Ground Reaction Force……..GRF

Knee Adduction Moment…….……KAM

Knee Adduction Moment Impulse…….……KAM-I

Knee Adduction Moment Rate…….……KAM-R

Knee Extension Moment……...KEM

Knee Flexion Moment……...KFM

Knee Flexion Moment Rate…….……..…KFM-R

Osteoarthritis……OA

Range of Motion……...ROM

Total Knee Arthroplasty……TKA

INTRODUCTION

Osteoarthritis (OA) is considered the most common joint disorder in the world with a majority of people exhibiting signs of OA by the age of 65 and 80% showing signs of OA by age 75.[1] Knee osteoarthritis is also considered the most common form of OA. In a study of 847 arthritic joints, 41.2% involved the knee indicating the importance of the implications of OA development and progression in this joint.[2] For patients with early to moderate knee OA, their first complaint often comes from their difficulty in negotiating stairs,[3] one of their many activities of daily living (ADL). In order to decrease pain and limitations during ADL, total knee arthroplasty (TKA) has become the standard treatment for individuals with knee OA leading to TKA procedures increasing in volume by 161.5% from 1991 to 2010.[4] TKA demand is expected to grow to nearly 3.5 million procedures by 2030 which includes revisions for patients with previous TKA procedures.[5] Available data suggest that 600,000 TKA procedures are performed in the United States each year costing approximately $15,000 per procedure, making it a $9 billion industry[4] and demonstrating the need for continued research related to OA and TKA. The development of OA typically manifests itself in reduced capability of an individual with TKA being the final option,[6] coming with biomechanical implications.

Limitations in ADL's have been associated with changes in biomechanical variables of interest. Knee flexion moment (KFM) has been a kinetic variable of interest to researchers since an increase in KFM in the early stance phase of the gait cycle, coupled with an increase in late stance knee extension moment (KEM) indicate improved impact attenuation and function at the knee.[7] The KFM has been considered in OA and TKA research as a key indicator of overall health, functionality, and recovery of the knee pre and post-TKA.[7–9] Research suggests that a high KFM is related to quality of living scores since an increase in KFM may help patients show improved

confidence in knee joint function, reduced muscle pain, and potentially improved muscle strength.[8] Additionally, knee adduction moment (KAM) variables are considered to be potential indicators in the onset and severity of knee OA and also predictors for needing TKA or TKA revision.[10] Many studies have analyzed gait biomechanics during ambulation and KAM has become increasingly relevant.[7,9,11–16] Although peak KAM only represents loading at a singular moment in time, it is believed to be a surrogate for loading in the medial compartment of the knee.[10] Originally, KAM variables were thought to decrease after TKA and remain low,[14] a desired outcome for medical professionals. However, it is unclear in the literature if high KAM variables, specifically KAM impulse (KAM-I), are risk factors for loss of medial tibial cartilage volume, a sign of OA onset.[17]

While peak kinetic variables of KAM, KFM, KEM, and vertical ground reaction force (vGRF) have been widely reported in knee OA research,[7,17–20] these variables only give insight into one particular aspect of mechanical loading. Variables examining force exposure over time may provide insight into the actual loads experienced on the knee. The KAM-I represents the total exposure of force on the frontal plane of the knee during the duration of foot contact with the ground. KAM-I can be defined as the net positive impulse of the KAM curve according to Doyle et al.[21] Additionally, while not studied to a great extent, KAM rate (KAM-R) represents the rate of force development. KAM-R is defined as the maximum instantaneous slope from foot contact to the first peak of the KAM curve.[21] Two authors previously concluded that KAM-R is the most sensitive measure of the following variables: KAM-R, peak KAM, KAM impulse, and KAM-R*magnitude.[21,22]

Therefore, the purpose of this study was twofold: 1) to compare proportional changes of each biomechanical variable from pre to post-TKA time points between walking, stair ascent, and

stair descent and 2) to determine the relationship between biomechanical variables and clinical ROM in walking, stair ascent, and stair descent pre- and post-TKA. We hypothesized that 1) changes in biomechanical variables of interest over time would be equally proportionate between the tasks of walking, stair ascent, and stair descent and 2) that biomechanical variables would be associated with clinical ROM at pre-TKA and discharge time points.

METHODOLOGY

Research Design

A longitudinal analysis of walking gait was performed during level ambulation and stair negotiation before and after participants underwent total knee arthroplasty. Participants attended five data collection sessions at 2-weeks pre-TKA, then 6-weeks, 3-months, 6-months, and 12-months post-TKA.

Participants

Inclusion criteria included: being under 75 years of age at the time of surgery; having no previous history of lower extremity fracture, osteotomy, or joint replacement; undergoing a unilateral or bilateral knee joint arthroplasty for the treatment of osteoarthritis; and being able to walk without an aid at each assessment. Exclusion criteria included: Participants never received a TKA prior to the procedure. Thirty adults (18 men, 12 women, aged 54-74 years) undergoing either unilateral (n= 19) or bilateral (n=11) TKA volunteered for this study.

All TKA surgeries were performed by the same board-certified orthopedic surgeon. Patients were randomly assigned to receive either a single radius (SR) (GetAroundKnee™, Stryker Orthopedics, Mahwah, NJ) or a multi-radius (MR) implant (Balanced Knee® System, Ortho Development Corporation, Draper, UT) design. Twenty knees received the SR implant

and twenty-one knees received the MR implant. For participants who underwent bilateral TKA, they received the same implant in both knees, whether SR or MR.

Prior to enrollment in the study, all participants signed informed consent forms approved by the University of Hawai‘i at Mānoa’s Institutional Review Board. Once consent was gained, participants received an ID number that was used for all data collection sessions and paperwork. All participant data were kept in a filing cabinet in a locked office within the Biomechanics Human Performance Lab at the University of Hawai‘i at Mānoa.

Instrumentation and Protocol

All gait analyses were completed in the Gait Laboratory at the University of Hawai‘i at Mānoa. Participants were instructed to wear comfortable clothing and athletic shoes for data collection. Upon arrival, participants had their height measured with a wall-mounted stadiometer (Seca, model no. 67032, Country Technology, Inc. Gays Mills, WI USA), and body mass was determined with a scale (Cardinal Detecto certified scale, model no. 442 Webb City, MO USA). Shank lengths were recorded as the distance measured from the lateral knee joint line to the distal lateral malleolus; 80% of shank length was calculated and marked. These markings served as location points for placement of the hand-held dynamometer during knee extensor strength testing, to allow for consistent placement of the dynamometer relative to each patient.

Thirty-one reflective markers were placed bilaterally over the 1st metatarsophalangeal joints (removed after calibration), 2nd metatarsophalangeal joints, 5th metatarsophalangeal joints, base of 5th metatarsal, medial malleolus (removed after calibration), lateral malleolus, posterior calcaneus, medial femoral epicondyles (removed after calibration), lateral femoral epicondyles, anterior superior iliac spines, posterior superior iliac spines, acromion joints, dorsum of foot, jugular notch, xiphoid process, C7 spinous process, T10, inferior angle of right

scapula, and four arrays at the bilateral femur (80% leg length), bilateral shank – lower leg (80% leg length).

Kinematic and kinetic data collection began with level ambulation towards an eye-level "X" on the wall that participants were instructed to look at during the duration of the ambulation. Participants were instructed to walk at a self-selected velocity and were placed in such a way as to strike the force plate (OR6 Series, model no. MCA 6. Advanced Mechanical Technology, Inc., Phoenix, AZ USA) with the surgical limb. Walking velocity was ascertained using Speedtrap II infrared sensors (Brower Timing System, infrared TC-Photographic timers Power Systems, Inc., Knoxville, TN USA) placed 4 meters apart and centered on the force plate.

A custom-built three-step staircase, with dimensions of an 18.5 cm step rise, 46.5 cm step width, and 28 cm step tread was used for assessing stair negotiation. Each participant was instructed to begin walking two meters before ascending the stairs using an alternating foot-fall pattern with the TKA limb contacting the ground and second-step. A handrail was available for participants who felt unstable, though use was discouraged and the trial was discarded if contact was made. A member of the research team was positioned at the bottom of the stairs at all times to provide further assistance if needed. Upon arriving at the third step on the staircase, participants were instructed to safely turn 180°, pause, and ambulate down the stairs. Subjects were instructed to contact the middle step and the floor with the surgical limb while following the same protocol during stair ascent to include not touching the handrail unless necessary to maintain balance. Stair descent required five successful trials to be completed.

Marker positions were collected using a Vicon Nexus motion capture system (Nexus 2.5.0 Vicon Motion Systems, Vicon LA, Culver City, CA USA). Eighteen motion capture cameras were used (7 MX T40-S, 6 MX 13, 5 MX 3+. Vicon Motion Systems, Vicon LA,

Culver City, CA USA). Two force plates, one inserted flush with the floor and one embedded within the second step of the stairs, were used to collect kinetic data on the TKA limb. Kinematic data were collected at 240 Hz and time synchronized with kinematic data collected at 960 Hz. A low-pass Butterworth filter was used to filter kinematic and kinetic data used for calculation of external joint moments at a 10 Hz cut-off frequency and ground reaction force data was filtered using a 50 Hz cut-off frequency. External joint moments were calculated using inverse dynamics based on filtered marker trajectories and kinetic data. Biomechanics data were processed using Visual 3D (C-Motion, Inc., Germantown, MD). Due to variability during stair negotiation in the OA population, five successful trials were taken.

All clinical ROM measurements were performed at Straub Medical Center, Hawai‘i Pacific Health. Range of Motion was measured pre-TKA by a physician approximately 4-months prior to the TKA procedure. Post-TKA ROM was measured within 24 hours following TKA by a physical therapist. The physician or physical therapist first measured knee extension. With the participant lying supine, the practitioner placed one hand on the participant’s heel and one hand on the thigh to apply only slight pressure to demonstrate a participant’s maximum passive knee extension. Similarly, knee flexion was passively measured with the participant in a supine position, with hip flexed to 90°. Range of motion was measured visually by the physician or physical therapist, with total range of motion calculated as the maximum flexion angle minus the maximum extension angle. The post-TKA protocol was identical to the pre-TKA.

Statistical Analysis

Descriptive statistics, including mean, standard deviation, and percent change for each time interval of pre-TKA to post-TKA were calculated (2-weeks pre-TKA, then 6-weeks, 3-months, 6-months, and 12-months post-TKA). To test the hypothesis that changes in

biomechanical variables of interest over time would be equally proportionate between the tasks of walking, stair ascent, and stair descent, data were assessed using multiple analysis of covariance (ANCOVA) tests and normality was assessed using Levene's test. Partial eta squared was calculated during ANCOVA analysis. Percent changes were calculated using the method published by Vickers[23] as it demonstrated the highest statistical power and was most efficient. Post hoc Bonferroni comparisons were made to determine where significant differences existed after significant main effects by group were found. This study used ANCOVA estimated means of each biomechanical variable (Table 6), minus the respective preoperative (pre-TKA) biomechanical variable mean, divided by the same preoperative biomechanical variable mean. The equation is described by the following:

$$Percent\ Change = \frac{(ANCOVA\ Estimated\ Mean - Preoperative\ Mean)}{Preoperative\ Mean} * 100$$

To test the second hypothesis that biomechanical variables would be associated with clinical ROM at pre-TKA and discharge time points, Pearson r correlations were used to determine relationships. Comparisons were made between either pre-TKA or post-TKA clinical ROM and each of the following: peak KAM, peak KAM-I, peak KAM-R, peak KFM, peak KFM-R, and varus velocity. All statistical procedures were conducted using SPSS (version 27; IBM Corp, Armonk, NY).

RESULTS

Participant demographics and sample sizes at each of the five time periods can be found in Table 1. Bonferroni's multiple comparisons for dependent measures revealed no significant differences between groups for age, height, weight, or BMI (Table 2). Group comparisons made were between walking, stair ascent, and stair descent. Interactions between the walking and stair ascent group and walking and stair descent group showed some influence of age, though insignificant ($p = 0.153$ pre-TKA, $p = 0.371$ 6-weeks post-TKA, $p = 0.482$ 3-months post-TKA, $p = 0.229$ 6-months post-TKA, and $p = 0.374$ 12-months post-TKA). Height, weight, and BMI interactions amongst all three groups were not significant.

Table 1

Participant Demographics ANOVA

		Pre-TKA (N = 97)		6-Weeks (N = 71)	
	Group	Mean ± SD	95% CI	Mean ± SD	95% CI
Age (years)	Total	64.7 ± 5.8	[63.5 65.8]	64.5 ± 6.0	[63.1 65.9]
Height (m)	Total	1.65 ± 0.09	[1.64 1.67]	1.66 ± 0.08	[1.64 1.68]
Weight (kg)	Total	81.3 ± 16.3	[78.1 84.6]	77.5 ± 16.7	[73.5 81.5]
BMI (kg/m²)	Total	29.6 ± 5.1	[28.6 30.6]	28.1 ± 5.2	[26.9 29.4]

		3-Months (N = 82)		6-Months (N = 98)	
	Group	Mean ± SD	95% CI	Mean ± SD	95% CI
Age (years)	Total	65.9 ± 4.5	[64.9 66.9]	65.6 ± 5.4	[64.5 66.7]
Height (m)	Total	1.64 ± 0.08	[1.62 1.66]	1.64 ± 0.08	[1.62 1.65]
Weight (kg)	Total	77.1 ± 16.5	[73.5 80.7]	76.8 ± 15.5	[73.7 79.9]
BMI (kg/m²)	Total	28.5 ± 5.2	[27.4 29.7]	28.6 ± 5.1	[27.6 29.7]

		12-Months (N = 106)	
	Group	Mean ± SD	95% CI
Age (years)	Total	65.6 ± 5.0	[64.6 66.6]
Height (m)	Total	1.64 ± 0.09	[1.62 1.66]
Weight (kg)	Total	81.3 ± 18.4	[77.8 84.8]
BMI (kg/m²)	Total	30.1 ± 5.7	[29.0 31.2]

Table 2

Bonferroni's Pairwise Comparison of Participant Demographics

		Pre-TKA				6-Weeks			
	Group	Mean Difference	Std. Error	95% CI	P-value	Mean Difference	Std. Error	95% CI	P-value
Age (years)	Walking/Ascent	2.3	1.3	[-1.0 5.6]	0.271	1.8	1.6	[-2.2 5.8]	0.802
	Walking/Descent	2.9	1.4	[-0.7 6.4]	0.153	3.0	1.9	[-1.7 7.6]	0.371
	Ascent/Descent	0.6	1.5	[-3.1 4.2]	1.000	1.2	2.0	[-3.8 6.1]	1.000
Height (m)	Walking/Ascent	0.0	0.0	[-0.1 0.0]	1.000	0.0	0.0	[0.0 0.1]	1.000
	Walking/Descent	0.0	0.0	[-0.1 0.0]	1.000	0.0	0.0	[-0.1 0.1]	1.000
	Ascent/Descent	0.0	0.0	[-0.1 0.0]	1.000	0.0	0.0	[-0.1 0.1]	1.000
Weight (kg)	Walking/Ascent	-2.4	3.9	[-11.9 7.1]	1.000	0.0	4.6	[-11.2 11.3]	1.000
	Walking/Descent	1.1	4.2	[-9.1 11.3]	1.000	1.2	5.4	[-12.0 14.4]	1.000
	Ascent/Descent	3.5	4.4	[-7.1 14.2]	1.000	1.2	5.7	[-12.9 15.3]	1.000
BMI (kg/m²)	Walking/Ascent	-0.4	1.2	[-3.3 2.6]	1.000	-0.2	1.4	[-3.7 3.3]	1.000
	Walking/Descent	1.1	1.3	[-2.1 4.2]	1.000	0.3	1.7	[-3.8 4.4]	1.000
	Ascent/Descent	1.4	1.4	[-1.9 4.7]	0.894	0.5	1.8	[-3.9 4.9]	1.000

		3-Months				6-Months			
	Group	Mean Difference	Std. Error	95% CI	P-value	Mean Difference	Std. Error	95% CI	P-value
Age (years)	Walking/Ascent	2.0	1.2	[-0.9 4.9]	0.294	1.9	1.3	[-1.3 5.1]	0.466
	Walking/Descent	1.7	1.2	[-1.3 4.7]	0.482	2.4	1.3	[-0.9 5.6]	0.229
	Ascent/Descent	-0.3	1.2	[-3.3 2.8]	1.000	0.5	1.3	[-2.8 3.8]	1.000
Height (m)	Walking/Ascent	0.0	0.0	[-0.1 0.1]	1.000	0.0	0.0	[0.0 0.1]	1.000
	Walking/Descent	0.0	0.0	[0.0 0.1]	1.000	0.0	0.0	[0.0 0.1]	1.000
	Ascent/Descent	0.0	0.0	[0.0 0.1]	1.000	0.0	0.0	[-0.1 0.1]	1.000
Weight (kg)	Walking/Ascent	0.3	4.4	[-10.5 11.1]	1.000	0.7	3.8	[-8.7 10.0]	1.000
	Walking/Descent	-0.2	4.6	[-11.4 10.9]	1.000	-0.4	3.9	[-9.8 9.1]	1.000
	Ascent/Descent	-0.6	4.6	[-11.8 10.7]	1.000	-1.0	3.9	[-10.6 8.5]	1.000
BMI (kg/m²)	Walking/Ascent	-0.1	1.4	[-3.5 3.4]	1.000	-0.1	1.3	[-3.1 3.0]	1.000
	Walking/Descent	-0.5	1.4	[-4.0 3.1]	1.000	-0.6	1.3	[-3.7 2.5]	1.000
	Ascent/Descent	-0.4	1.4	[-3.9 3.1]	1.000	-0.5	1.3	[-3.6 2.6]	1.000

		12-Months			
	Group	Mean Difference	Std. Error	95% CI	P-value
Age (years)	Walking/Ascent	1.6	1.2	[-1.3 4.5]	0.550
	Walking/Descent	1.8	1.2	[-1.1 4.8]	0.374
	Ascent/Descent	0.3	1.2	[-2.7 3.2]	1.000
Height (m)	Walking/Ascent	0.0	0.0	[0.0 0.1]	1.000
	Walking/Descent	0.0	0.0	[0.0 0.1]	1.000
	Ascent/Descent	0.0	0.0	[0.0 0.1]	1.000
Weight (kg)	Walking/Ascent	1.4	4.4	[-9.2 12.0]	1.000
	Walking/Descent	-1.5	4.4	[-12.2 9.2]	1.000
	Ascent/Descent	-2.9	4.5	[-13.8 7.9]	1.000
BMI (kg/m²)	Walking/Ascent	0.5	1.4	[-2.8 3.7]	1.000
	Walking/Descent	-0.8	1.4	[-4.1 2.6]	1.000
	Ascent/Descent	-1.2	1.4	[-4.6 2.1]	1.000

Percent Change

Table 3 presents the ANCOVA mean and standard deviations of biomechanical variables for each of the four post-TKA data collection time points. Table 4 presents the ANCOVA tests of between-subject effects for the covariates, where the covariates were always the baseline for each measured biomechanical variable and for group interactions. All covariates were significant except for peak KAM at 3-months, peak KAM-R at 3-months, and varus velocity at 3-months, 6-months, and 12-months. Group differences varied and can be found in the referenced Table 4. Percent change analysis revealed KAM-R and KAM-I to have significant Levene's at 6-weeks, 3-months, 6-months, and 12-months post-TKA. KFM and varus velocity also indicated significant Levene's at the 3-month and 6-month post-TKA time periods.

Table 3

ANCOVA Mean and Standard Deviations of Peak Biomechanical Variables

	Pre-TKA		
	Walking (N = 40)	Ascent (N = 32)	Descent (N = 25)
KAM (N*m/kg)	0.46 ± 0.22	0.49 ± 0.24	0.58 ± 0.28
KAM-R (N*m/kg/s)	2.29 ± 1.70	0.81 ± 0.41	2.95 ± 2.08
KAM-I (∫N*m*s/kg)	0.23 ± 0.13	0.27 ± 0.21	0.35 ± 0.29
KFM (N*m/kg)	0.66 ± 0.51	0.63 ± 0.24	0.90 ± 0.38
KFM-R (N*m/kg/s)	2.68 ± 2.01	3.60 ± 4.43	4.45 ± 3.21
Varus Velocity (°/s)	90.19 ± 30.71	64.90 ± 25.86	47.76 ± 63.12

	6-Weeks		
	Walking (N = 34)	Ascent (N = 20)	Descent (N = 13)
KAM (N*m/kg)	0.27 ± 0.13	0.32 ± 0.12	0.30 ± 0.11
KAM-R (N*m/kg/s)	1.42 ± 0.79	0.64 ± 0.28	1.26 ± 0.71
KAM-I (∫N*m*s/kg)	0.15 ± 0.06	0.16 ± 0.09	0.14 ± 0.08
KFM (N*m/kg)	0.53 ± 0.23	0.48 ± 0.24	0.82 ± 0.21
KFM-R (N*m/kg/s)	2.24 ± 1.47	2.28 ± 1.41	2.73 ± 1.27
Varus Velocity (°/s)	76.77 ± 32.33	67.25 ± 45.85	44.45 ± 30.43

	3-Months		
	Walking (N = 29)	Ascent (N = 24)	Descent (N = 19)
KAM (N*m/kg)	0.32 ± 0.14	0.34 ± 0.15	0.37 ± 0.13
KAM-R (N*m/kg/s)	1.83 ± 1.10	0.77 ± 0.43	1.74 ± 0.89
KAM-I (∫N*m*s/kg)	0.14 ± 0.06	0.15 ± 0.11	0.20 ± 0.16
KFM (N*m/kg)	0.59 ± 0.23	0.53 ± 0.20	0.53 ± 0.20
KFM-R (N*m/kg/s)	2.93 ± 1.77	2.85 ± 1.27	4.51 ± 2.39
Varus Velocity (°/s)	88.78 ± 37.80	74.36 ± 40.20	33.37 ± 14.48

	6-Months		
	Walking (N = 34)	Ascent (N = 25)	Descent (N = 23)
KAM (N*m/kg)	0.36 ± 0.13	0.37 ± 0.14	0.39 ± 0.18
KAM-R (N*m/kg/s)	2.17 ± 1.35	0.91 ± 0.51	2.19 ± 1.46
KAM-I (∫N*m*s/kg)	0.15 ± 0.05	0.16 ± 0.09	0.18 ± 0.12
KFM (N*m/kg)	0.65 ± 0.24	0.59 ± 0.18	0.93 ± 0.26
KFM-R (N*m/kg/s)	3.62 ± 2.13	3.37 ± 1.62	4.92 ± 2.49
Varus Velocity (°/s)	81.38 ± 29.60	64.44 ± 20.41	23.32 ± 18.62

	12-Months		
	Walking (N = 37)	Ascent (N = 27)	Descent (N = 22)
KAM (N*m/kg)	0.32 ± 0.09	0.35 ± 0.14	0.36 ± 0.15
KAM-R (N*m/kg/s)	1.73 ± 0.81	0.77 ± 0.41	2.03 ± 1.28
KAM-I (∫N*m*s/kg)	0.14 ± 0.05	0.16 ± 0.10	0.16 ± 0.11
KFM (N*m/kg)	0.68 ± 0.22	0.65 ± 0.20	1.05 ± 0.25
KFM-R (N*m/kg/s)	3.23 ± 1.86	3.23 ± 1.51	5.65 ± 2.38
Varus Velocity (°/s)	83.75 ± 31.93	67.50 ± 33.34	29.25 ± 25.63

Table 4

ANCOVA Tests of Between-Subject Effects of pre-TKA Biomechanical Variable as Covariate

	6-Weeks				3-Months		
	Source	F	Sig.	Partial Eta Squared	F	Sig.	Partial Eta Squared
Peak KAM	Covariate - Baseline	4.15	0.05	0.06	3.10	0.08	0.04
	Group	0.70	0.50	0.02	0.43	0.65	0.01
Peak KAM-R	Covariate - Baseline	18.44	0.00	0.23	1.31	0.26	0.02
	Group	3.86	0.03	0.11	6.25	0.00	0.16
Peak KAM-I	Covariate - Baseline	9.99	0.00	0.14	25.82	0.00	0.28
	Group	0.54	0.59	0.02	0.40	0.67	0.01
Peak KFM	Covariate - Baseline	14.53	0.00	0.19	31.28	0.00	0.32
	Group	8.64	0.00	0.22	11.64	0.00	0.25
Peak KFM-R	Covariate - Baseline	17.31	0.00	0.22	13.91	0.00	0.17
	Group	1.03	0.36	0.03	5.02	0.01	0.13
Varus Velocity	Covariate - Baseline	5.94	0.02	0.09	0.02	0.88	0.00
	Group	2.05	0.14	0.06	13.35	0.00	0.28

	6-Months				12-Months		
	Source	F	Sig.	Partial Eta Squared	F	Sig.	Partial Eta Squared
Peak KAM	Covariate - Baseline	14.20	0.00	0.15	14.09	0.00	0.15
	Group	0.00	1.00	0.00	0.51	0.60	0.01
Peak KAM-R	Covariate - Baseline	9.47	0.00	0.11	7.00	0.01	0.08
	Group	3.59	0.03	0.08	6.27	0.00	0.13
Peak KAM-I	Covariate - Baseline	41.14	0.00	0.35	51.45	0.00	0.39
	Group	0.01	0.99	0.00	1.00	0.37	0.02
Peak KFM	Covariate - Baseline	35.98	0.00	0.32	5.85	0.02	0.07
	Group	8.22	0.00	0.17	18.04	0.00	0.31
Peak KFM-R	Covariate - Baseline	17.61	0.00	0.18	8.78	0.00	0.10
	Group	3.96	0.02	0.09	10.77	0.00	0.21
Varus Velocity	Covariate - Baseline	3.11	0.08	0.04	0.08	0.77	0.00
	Group	30.40	0.00	0.44	18.45	0.00	0.31

Results of Bonferroni's multiple comparisons between groups for the ANCOVA revealed twenty-five significant data points. The results from the post hoc Bonferroni's multiple pairwise comparisons between groups can be found in Table 5. The mean difference of peak KAM-R between the walking and ascent groups was significant at 6-weeks ($p = 0.031$), 3-months ($p = 0.003$), 6-months ($p = 0.031$), and 12-months (0.010) using pre-TKA peak KAM-R as the covariate. The mean difference of peak KAM-R between the ascent and descent groups was significant at 3-months ($p = 0.034$) and 12-months ($p = 0.004$) using pre-TKA peak KAM-R as the covariate. The mean difference of peak KFM between the walking and descent groups was

significant at 6-weeks ($p = 0.002$), 3-months ($p = 0.001$), 6-months ($p = 0.014$), and 12-months ($p = 0.000$) using pre-TKA peak KFM as the covariate. The mean difference of peak KFM between the ascent and descent groups was also significant at 6-weeks ($p = 0.001$), 3-months ($p = 0.000$), 6-months ($p = 0.000$), and 12-months ($p = 0.000$) using pre-TKA peak KFM as the covariate. The mean difference of peak KFM-R between the walking and descent groups was significant at 3-months ($p = 0.033$) and 12-months ($p = 0.000$) using pre-TKA peak KFM-R as the covariate. The mean difference of peak KFM-R between the ascent and descent groups was significant at 3-months ($p = 0.012$), 6-months ($p = 0.021$), and 12-months ($p = 0.000$) using pre-TKA peak KFM-R as the covariate. The mean difference of varus velocity between the walking and descent groups was significant at 3-months ($p = 0.000$), 6-months ($p = 0.000$), and 12-months ($p = 0.000$) using pre-TKA varus velocity as the covariate. The mean difference of varus velocity between the ascent and descent groups was significant at 3-months ($p = 0.001$), 6-months ($p = 0.000$), and 12-months using pre-TKA varus velocity as the covariate.

Table 6 includes the ANCOVA estimated marginal means which were used as the post-TKA (final) values for the percent change calculations. Finally, Table 7 shows the calculated percent changes for each of the post-TKA measures compared to the respective pre-TKA measures.

Table 5

Bonferroni's Multiple Pairwise Comparisons Between Groups for ANCOVA

		Pre-TKA to 6-Weeks				Pre-TKA to 3-Months			
	Group	Mean Difference	Std. Error	P-value	95% CI	Mean Difference	Std. Error	P-value	95% CI
Peak KAM	Walking/Ascent	-0.040	0.034	0.721	-0.124 , 0.043	-0.015	0.038	1.000	-0.108 , 0.078
	Walking/Descent	-0.016	0.040	1.000	-0.113 , 0.082	-0.038	0.041	1.000	-0.139 , 0.062
	Ascent/Descent	0.025	0.043	1.000	-0.081 , 0.131	-0.023	0.042	1.000	-0.127 , 0.081
KAM-R	Walking/Ascent	**0.476***	0.180	**0.031**	0.033 , 0.919	**0.925***	0.266	**0.003**	0.271 , 1.578
	Walking/Descent	0.282	0.193	0.448	-0.193 , 0.758	0.132	0.259	1.000	-0.503 , 0.767
	Ascent/Descent	-0.194	0.231	1.000	-0.762 , 0.375	**-0.793***	0.305	**0.034**	-1.541 , -0.046
Peak KAM-I	Walking/Ascent	-0.009	0.020	1.000	-0.058 , 0.041	-0.001	0.026	1.000	-0.066 , 0.064
	Walking/Descent	0.018	0.024	1.000	-0.040 , 0.076	-0.024	0.029	1.000	-0.095 , 0.047
	Ascent/Descent	0.026	0.026	0.916	-0.037 , 0.090	-0.023	0.030	1.000	-0.096 , 0.050
Peak KFM	Walking/Ascent	0.048	0.058	1.000	-0.095 , 0.192	0.065	0.050	0.599	-0.058 , 0.187
	Walking/Descent	**-0.247***	0.069	**0.002**	-0.416 , -0.078	**-0.219***	0.058	**0.001**	-0.360 , -0.077
	Ascent/Descent	**-0.296***	0.075	**0.001**	-0.480 , -0.112	**-0.283***	0.060	**0.000**	-0.430 , -0.136
Peak KFM-R	Walking/Ascent	0.321	0.367	1.000	-0.583 , 1.224	0.230	0.461	1.000	-0.903 , 1.362
	Walking/Descent	-0.326	0.415	1.000	-1.347 , 0.694	**-1.299***	0.497	**0.033**	-2.519 , -0.078
	Ascent/Descent	-0.647	0.454	0.477	-1.763 , 0.469	**-1.528***	0.513	**0.012**	-2.787 , -0.269
Varus Velocity	Walking/Ascent	4.632	10.128	1.000	-20.279 , 29.543	14.073	9.802	0.467	-9.988 , 38.134
	Walking/Descent	24.031	11.981	0.148	-5.437 , 53.499	**54.856***	10.846	**0.000**	28.234 , 81.478
	Ascent/Descent	19.399	12.627	0.388	-11.659 , 50.457	**40.783***	10.685	**0.001**	14.555 , 67.011

		Pre-TKA to 6-Months				Pre-TKA to 12-Months			
	Group	Mean Difference	Std. Error	P-value	95% CI	Mean Difference	Std. Error	P-value	95% CI
Peak KAM	Walking/Ascent	0.001	0.036	1.000	-0.088 , 0.090	-0.029	0.030	1.000	-0.101 , 0.044
	Walking/Descent	-0.002	0.038	1.000	-0.095 , 0.091	-0.021	0.032	1.000	-0.099 , 0.058
	Ascent/Descent	-0.003	0.040	1.000	-0.101 , 0.096	0.008	0.034	1.000	-0.075 , 0.091
KAM-R	Walking/Ascent	**0.858***	0.327	**0.031**	0.058 , 1.658	**0.703***	0.232	**0.010**	0.135 , 1.270
	Walking/Descent	0.105	0.310	1.000	-0.654 , 0.864	-0.203	0.228	1.000	-0.761 , 0.354
	Ascent/Descent	-0.753	0.371	0.137	-1.661 , 0.155	**-0.906***	0.275	**0.004**	-1.577 , -0.235
Peak KAM-I	Walking/Ascent	-0.002	0.019	1.000	-0.047 , 0.044	-0.010	0.018	1.000	-0.053 , 0.032
	Walking/Descent	0.001	0.020	1.000	-0.047 , 0.049	0.018	0.019	1.000	-0.029 , 0.065
	Ascent/Descent	0.002	0.021	1.000	-0.048 , 0.053	0.028	0.020	0.489	-0.021 , 0.077
Peak KFM	Walking/Ascent	0.071	0.050	0.475	-0.051 , 0.194	0.015	0.055	1.000	-0.120 , 0.150
	Walking/Descent	**-0.160***	0.055	**0.014**	-0.295 , -0.026	**-0.333***	0.061	**0.000**	-0.480 , -0.185
	Ascent/Descent	**-0.232***	0.058	**0.000**	-0.373 , -0.090	**-0.347***	0.066	**0.000**	-0.507 , -0.187
Peak KFM-R	Walking/Ascent	0.502	0.507	0.973	-0.737 , 1.742	0.118	0.464	1.000	-1.017 , 1.253
	Walking/Descent	-1.023	0.520	0.157	-2.295 , 0.248	**-2.088***	0.505	**0.000**	-3.322 , -0.854
	Ascent/Descent	**-1.526***	0.552	**0.021**	-2.875 , -0.176	**-2.206***	0.530	**0.000**	-3.501 , -0.910
Varus Velocity	Walking/Ascent	14.701	6.436	0.075	-1.046 , 30.448	15.669	8.127	0.172	-4.194 , 35.532
	Walking/Descent	**53.512***	6.962	**0.000**	36.478 , 70.546	**53.619***	8.913	**0.000**	31.836 , 75.402
	Ascent/Descent	**38.811***	7.044	**0.000**	21.577 , 56.045	**37.950***	8.994	**0.000**	15.969 , 59.931

*. The mean difference is significant at the .05 level.

Table 6

ANCOVA Estimated Marginal Means

		6-Weeks			3-Months		
	Group	Mean	Std. Error	95% CI	Mean	Std. Error	95% CI
Peak KAM	Walking	0.276	0.021	0.235 - 0.318	0.323	0.026	0.273 - 0.374
	Ascent	0.317	0.027	0.263 - 0.370	0.338	0.028	0.283 - 0.394
	Descent	0.292	0.034	0.225 - 0.359	0.361	0.032	0.298 - 0.425
Peak KAM-R	Walking	1.354	0.102	1.151 - 1.558	1.797	0.164	1.469 - 2.125
	Ascent	0.879	0.142	0.594 - 1.163	0.872	0.197	0.479 - 1.265
	Descent	1.072	0.168	0.735 - 1.409	1.665	0.209	1.249 - 2.082
Peak KAM-I	Walking	0.153	0.012	0.128 - 0.177	0.155	0.018	0.120 - 0.191
	Ascent	0.161	0.016	0.129 - 0.193	0.157	0.020	0.118 - 0.196
	Descent	0.135	0.020	0.095 - 0.175	0.179	0.022	0.135 - 0.224
Peak KFM	Walking	0.537	0.036	0.466 - 0.608	0.624	0.034	0.556 - 0.692
	Ascent	0.489	0.046	0.396 - 0.582	0.560	0.037	0.485 - 0.635
	Descent	0.784	0.058	0.668 - 0.901	0.843	0.045	0.754 - 0.932
Peak KFM-R	Walking	2.381	0.220	1.941 - 2.820	3.053	0.311	2.432 - 3.674
	Ascent	2.060	0.288	1.484 - 2.636	2.823	0.340	2.145 - 3.502
	Descent	2.707	0.351	2.005 - 3.409	4.352	0.384	3.585 - 5.119
Varus Velocity	Walking	73.705	6.171	61.372 - 86.037	88.517	6.645	75.258 - 101.776
	Ascent	69.072	7.913	53.260 - 84.884	74.444	7.065	60.346 - 88.541
	Descent	49.673	10.003	29.685 - 69.662	33.661	8.156	17.386 - 49.936

		6-Months			12-Months		
	Group	Mean	Std. Error	95% CI	Mean	Std. Error	95% CI
Peak KAM	Walking	0.370	0.024	0.323 - 0.417	0.325	0.019	0.286 - 0.363
	Ascent	0.369	0.028	0.314 - 0.424	0.353	0.023	0.308 - 0.398
	Descent	0.372	0.029	0.314 - 0.430	0.345	0.025	0.295 - 0.396
Peak KAM-R	Walking	2.085	0.197	1.692 - 2.478	1.676	0.139	1.400 - 1.953
	Ascent	1.226	0.250	0.729 - 1.723	0.974	0.178	0.620 - 1.327
	Descent	1.980	0.247	1.487 - 2.472	1.880	0.187	1.507 - 2.253
Peak KAM-I	Walking	0.162	0.012	0.138 - 0.186	0.154	0.011	0.131 - 0.177
	Ascent	0.163	0.014	0.135 - 0.191	0.164	0.013	0.138 - 0.191
	Descent	0.161	0.015	0.131 - 0.191	0.136	0.015	0.106 - 0.166
Peak KFM	Walking	0.689	0.033	0.623 - 0.755	0.685	0.036	0.613 - 0.756
	Ascent	0.618	0.038	0.541 - 0.694	0.670	0.042	0.585 - 0.754
	Descent	0.849	0.042	0.766 - 0.933	1.017	0.048	0.922 - 1.113
Peak KFM-R	Walking	3.773	0.330	3.117 - 4.429	3.353	0.303	2.750 - 3.956
	Ascent	3.271	0.383	2.509 - 4.032	3.235	0.352	2.535 - 3.935
	Descent	4.797	0.399	4.002 - 5.591	5.441	0.396	4.653 - 6.229
Varus Velocity	Walking	79.422	4.255	70.951 - 87.893	83.341	5.305	72.787 - 93.895
	Ascent	64.721	4.793	55.179 - 74.263	67.672	6.016	55.703 - 79.640
	Descent	25.910	5.206	15.546 - 36.275	29.722	6.831	16.133 - 43.311

Table 7

Percent Change Descriptive Statistics Calculated Via Covariate Estimated Means

	Pre-TKA to 6-Weeks			Pre-TKA to 3-Months		
	Walking	Ascent	Descent	Walking	Ascent	Descent
Peak KAM (N*m/kg)	-39.5%	-35.3%	-50.0%	-29.2%	-31.1%	-38.2%
Peak KAM-R (N*m/kg/s)	-40.8%	9.0%	-63.6%	-21.5%	8.1%	-43.5%
Peak KAM-I (∫N*m*s/kg)	-33.1%	-40.9%	-61.5%	-32.2%	-42.4%	-49.0%
Peak KFM (N*m/kg)	-18.0%	-22.2%	-13.1%	4.7%	-10.9%	-6.6%
Peak KFM-R (N*m/kg/s)	-11.1%	-42.8%	-39.1%	14.0%	-21.6%	-2.1%
Peak Varus Velocity (°/s)	-18.3%	6.4%	3.8%	-1.9%	14.7%	-29.6%
	Pre-TKA to 6-Months			Pre-TKA to 12-Months		
Peak KAM (N*m/kg)	-18.9%	-24.7%	-36.3%	-28.8%	-28.0%	-40.9%
Peak KAM-R (N*m/kg/s)	-8.9%	52.0%	-32.8%	-26.8%	20.8%	-36.2%
Peak KAM-I (∫N*m*s/kg)	-29.1%	-40.1%	-54.1%	-32.6%	-39.8%	-61.3%
Peak KFM (N*m/kg)	5.3%	-1.6%	-5.9%	4.7%	6.7%	12.7%
Peak KFM-R (N*m/kg/s)	40.8%	-9.1%	7.9%	25.2%	-10.1%	22.4%
Peak Varus Velocity (°/s)	-11.9%	-0.3%	-45.8%	-7.6%	4.3%	-37.9%

Correlation

Descriptive statistics used for Pearson Correlation analysis can be found in Table 8 while the correlation results between clinical ROM and pre-TKA biomechanical variables can be found in Tables 9, 10, and 11. Of the 108 correlations performed, there were fifteen significant correlations either at the 0.01 or 0.05 level. No significant correlations were found between pre-TKA biomechanical variables and ROM during walking or stair ascent (Table 9); however, two correlations were significant during stair descent. Peak KFM during descent was negatively correlated with post-TKA clinical ROM ($n = 25$, $r = -0.598$, $p = 0.002$). Similarly, peak KFM-R was negatively correlated with post-TKA clinical ROM during stair descent ($n = 25$, $r = -0.491$, $p = 0.013$).

Correlations between clinical ROM and biomechanical variables at 6-months post-TKA (Table 10) yielded seven significant values. Of consequence during level walking was peak varus velocity correlated to pre-TKA clinical ROM ($n = 34$, $r = -0.522$, $p = 0.002$), and peak KFM correlated to post-TKA clinical ROM ($n = 34$, $r = -0.398$, $p = 0.020$). During stair ascent, the following three variables were negatively correlated with pre-TKA clinical ROM: peak KAM (n

= 33, r = -0.391, p = 0.025), peak KAM-R (n = 33, r = -0.390, p = 0.025), and peak KAM-I (n = 33, r = -0.465, p = 0.006). During stair descent at 6-months, peak KAM-R was significantly correlated to pre-TKA clinical ROM (n = 31, r = -0.365, p = 0.043) while peak KFM was correlated to post-TKA clinical ROM (n = 31, r = -0.416, p = 0.022).

Correlations between clinical ROM and biomechanical variables at 12-months (Table 11) post-TKA generated six significant relationships. During walking, peak varus velocity was negatively correlated with pre-TKA clinical ROM (n = 37, r = -0.476, p = 0.003). During stair ascent, peak KAM-R was negatively correlated with pre-TKA clinical ROM (n = 35, r = -0.455, p = 0.006). Finally, during stair descent, all four correlations were negative relating to post-TKA clinical ROM, peak KAM (n = 34, r = -0.448, p = 0.008), peak KAM-R (n = 34, r = -0.530, p = 0.001), peak KFM (n = 34, r = -0.523, p = 0.001), and peak KFM-R (n = 34, r = -0.419, p = 0.014).

Table 8

Mean and Standard Deviations of Biomechanical Variables

	Pre-TKA		
	Walking (N = 40)	Ascent (N = 32)	Descent (N = 25)
Pre-TKA Clinical ROM (°)	115.63 ± 16.49	115.63 ± 16.49	116.79 ± 14.93
Post-TKA Clinical ROM (°)	60.35 ± 24.00	60.35 ± 24.00	61.13 ± 23.79
Peak KAM (N*m/kg)	0.52 ± 0.22	0.49 ± 0.24	0.58 ± 0.28
Peak KAM-R (N*m/kg/s)	2.29 ± 1.70	0.81 ± 0.41	2.95 ± 2.07
Peak KAM-I (∫N*m*s/kg)	0.23 ± 0.13	0.27 ± 0.21	0.35 ± 0.29
Peak KFM (N*m/kg)	0.65 ± 0.51	0.63 ± 0.24	0.90 ± 0.38
Peak KFM-R (N*m/kg/s)	2.68 ± 2.01	3.60 ± 4.43	4.45 ± 3.21
Peak Varus Velocity (°/s)	90.19 ± 30.71	64.90 ± 25.86	47.84 ± 63.06
	6-Weeks		
	Walking (N = 34)	Ascent (N = 22)	Descent (N = 14)
Peak KAM (N*m/kg)	0.27 ± 0.13	0.32 ± 0.11	0.30 ± 0.11
Peak KAM-R (N*m/kg/s)	1.42 ± 0.79	0.63 ± 0.27	1.20 ± 0.71
Peak KAM-I (∫N*m*s/kg)	0.15 ± 0.06	0.17 ± 0.10	0.15 ± 0.09
Peak KFM (N*m/kg)	0.53 ± 0.23	0.48 ± 0.22	0.81 ± 0.20
Peak KFM-R (N*m/kg/s)	2.24 ± 1.47	2.14 ± 1.41	2.59 ± 1.33
Peak Varus Velocity (°/s)	76.77 ± 32.33	67.10 ± 44.68	43.62 ± 29.40
	3-Months		
	Walking (N = 29)	Ascent (N = 28)	Descent (N = 25)
Peak KAM (N*m/kg)	0.32 ± 0.14	0.35 ± 0.14	0.40 ± 0.14
Peak KAM-R (N*m/kg/s)	1.83 ± 1.10	0.77 ± 0.41	1.82 ± 0.92
Peak KAM-I (∫N*m*s/kg)	0.14 ± 0.06	0.16 ± 0.12	0.24 ± 0.17
Peak KFM (N*m/kg)	0.59 ± 0.23	0.54 ± 0.20	0.91 ± 0.25
Peak KFM-R (N*m/kg/s)	2.93 ± 1.77	2.75 ± 1.22	3.91 ± 2.40
Peak Varus Velocity (°/s)	88.78 ± 37.80	73.47 ± 37.27	38.24 ± 29.18
	6-Months		
	Walking (N = 34)	Ascent (N = 33)	Descent (N = 31)
Peak KAM (N*m/kg)	0.39 ± 0.12	0.37 ± 0.13	0.39 ± 0.16
Peak KAM-R (N*m/kg/s)	2.17 ± 1.35	0.87 ± 0.47	1.98 ± 1.34
Peak KAM-I (∫N*m*s/kg)	0.15 ± 0.05	0.17 ± 0.09	0.19 ± 0.11
Peak KFM (N*m/kg)	0.65 ± 0.24	0.60 ± 0.17	0.96 ± 0.24
Peak KFM-R (N*m/kg/s)	3.62 ± 2.13	3.24 ± 1.54	4.52 ± 2.40
Peak Varus Velocity (°/s)	81.38 ± 29.60	65.35 ± 20.37	27.87 ± 20.20
	12-Months		
	Walking (N = 37)	Ascent (N = 35)	Descent (N = 34)
Peak KAM (N*m/kg)	0.37 ± 0.09	0.35 ± 0.13	0.43 ± 0.38
Peak KAM-R (N*m/kg/s)	1.73 ± 0.81	0.77 ± 0.36	3.12 ± 7.36
Peak KAM-I (∫N*m*s/kg)	0.14 ± 0.05	0.17 ± 0.09	0.18 ± 0.11
Peak KFM (N*m/kg)	0.68 ± 0.22	0.68 ± 0.19	1.05 ± 0.28
Peak KFM-R (N*m/kg/s)	1.73 ± 0.81	3.30 ± 1.54	5.21 ± 2.98
Peak Varus Velocity (°/s)	83.75 ± 31.93	68.13 ± 30.68	33.35 ± 24.89

Table 9

Correlations between Clinical ROM and Pre-TKA Peak Biomechanical Variables

Walking (N = 40)

	Pre-TKA Clinical ROM		Post-TKA Clinical ROM	
	R-value	P-value	R-value	P-value
KAM (N*m/kg)	-0.081	0.617	0.204	0.207
KAM-R (N*m/kg/s)	0.007	0.967	0.300	0.060
KAM-I (∫N*m*s/kg)	-0.090	0.580	0.121	0.455
KFM (N*m/kg)	-0.198	0.220	-0.132	0.416
KFM-R (N*m/kg/s)	-0.066	0.688	0.047	0.772
Varus Velocity (°/s)	0.113	0.489	0.053	0.745

Ascent (N = 32)

	Pre-TKA Clinical ROM		Post-TKA Clinical ROM	
	R-value	P-value	R-value	P-value
KAM (N*m/kg)	-0.184	0.312	0.140	0.444
KAM-R (N*m/kg/s)	-0.151	0.411	0.082	0.656
KAM-I (∫N*m*s/kg)	-0.295	0.101	0.023	0.903
KFM (N*m/kg)	0.018	0.922	-0.251	0.165
KFM-R (N*m/kg/s)	-0.210	0.248	0.074	0.686
Varus Velocity (°/s)	-0.096	0.602	0.180	0.323

Descent (N = 25)

	Pre-TKA Clinical ROM		Post-TKA Clinical ROM	
	R-value	P-value	R-value	P-value
KAM (N*m/kg)	-0.321	0.118	0.270	0.192
KAM-R (N*m/kg/s)	-0.376	0.064	0.234	0.260
KAM-I (∫N*m*s/kg)	-0.370	0.069	-0.020	0.924
KFM (N*m/kg)	-0.260	0.209	-.598**	0.002
KFM-R (N*m/kg/s)	-0.335	0.102	-.491*	0.013
Varus Velocity (°/s)	-0.137	0.514	-0.130	0.536

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 10

Correlations between Clinical ROM and Peak Biomechanical Variables at 6-Months

Walking (N = 34)

	Pre-TKA Clinical ROM		Post-TKA Clinical ROM	
	R-value	P-value	R-value	P-value
KAM (N*m/kg)	-0.279	0.110	-0.069	0.700
KAM-R (N*m/kg/s)	-0.261	0.136	-0.071	0.688
KAM-I (∫N*m*s/kg)	-0.254	0.146	-0.035	0.846
KFM (N*m/kg)	-0.038	0.830	-.398*	0.020
KFM-R (N*m/kg/s)	-0.101	0.570	-0.218	0.215
Varus Velocity (°/s)	-.522**	0.002	-0.171	0.332

Ascent (N = 33)

	Pre-TKA Clinical ROM		Post-TKA Clinical ROM	
	R-value	P-value	R-value	P-value
KAM (N*m/kg)	-0.391*	0.025	-0.021	0.909
KAM-R (N*m/kg/s)	-0.390*	0.025	0.015	0.932
KAM-I (∫N*m*s/kg)	-0.465**	0.006	-0.017	0.923
KFM (N*m/kg)	0.223	0.213	0.031	0.863
KFM-R (N*m/kg/s)	0.276	0.120	0.029	0.871
Varus Velocity (°/s)	-0.317	0.072	-0.108	0.551

Descent (N = 31)

	Pre-TKA Clinical ROM		Post-TKA Clinical ROM	
	R-value	P-value	R-value	P-value
KAM (N*m/kg)	-0.244	0.186	0.155	0.404
KAM-R (N*m/kg/s)	-0.365*	0.043	0.192	0.302
KAM-I (∫N*m*s/kg)	-0.205	0.269	0.052	0.782
KFM (N*m/kg)	-0.057	0.763	-0.416*	0.022
KFM-R (N*m/kg/s)	-0.273	0.137	-0.313	0.086
Varus Velocity (°/s)	-0.234	0.205	-0.341	0.061

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 11

Correlations between Clinical ROM and Peak Biomechanical Variables at 12-Months

Walking (N = 37)	Pre-TKA Clinical ROM		Post-TKA Clinical ROM	
	R-value	P-value	R-value	P-value
KAM (N*m/kg)	-0.122	0.472	-0.021	0.901
KAM-R (N*m/kg/s)	-0.221	0.189	-0.002	0.992
KAM-I (∫N*m*s/kg)	-0.106	0.531	-0.010	0.952
KFM (N*m/kg)	0.011	0.948	-0.092	0.588
KFM-R (N*m/kg/s)	-0.083	0.624	-0.083	0.627
Varus Velocity (°/s)	-0.476**	0.003	-0.070	0.682

Ascent (N = 35)	Pre-TKA Clinical ROM		Post-TKA Clinical ROM	
	R-value	P-value	R-value	P-value
KAM (N*m/kg)	-0.281	0.102	0.009	0.962
KAM-R (N*m/kg/s)	-0.455**	0.006	-0.009	0.959
KAM-I (∫N*m*s/kg)	-0.301	0.079	0.042	0.812
KFM (N*m/kg)	0.261	0.130	0.194	0.265
KFM-R (N*m/kg/s)	0.259	0.133	0.308	0.072
Varus Velocity (°/s)	-0.227	0.191	-0.070	0.691

Descent (N = 34)	Pre-TKA Clinical ROM		Post-TKA Clinical ROM	
	R-value	P-value	R-value	P-value
KAM (N*m/kg)	-0.280	0.109	-0.448**	0.008
KAM-R (N*m/kg/s)	-0.222	0.208	-0.530**	0.001
KAM-I (∫N*m*s/kg)	-0.284	0.103	0.035	0.845
KFM (N*m/kg)	-0.044	0.804	-0.523**	0.001
KFM-R (N*m/kg/s)	-0.168	0.343	-0.419*	0.014
Varus Velocity (°/s)	-0.084	0.636	-0.125	0.480

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

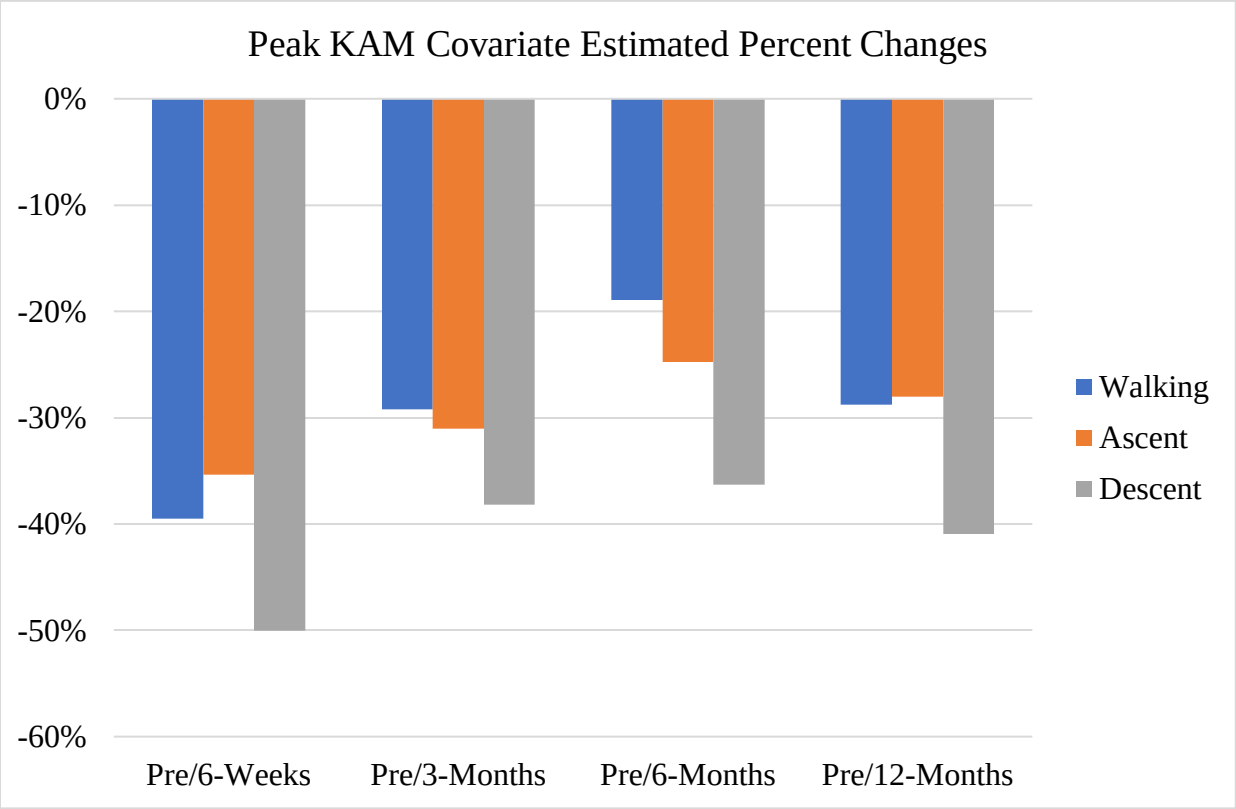

Figure 1. Illustrates peak KAM percent changes using ANCOVA estimated means during walking, stair ascent, and stair descent comparing from pre-TKA to each of the four post-TKA time points.

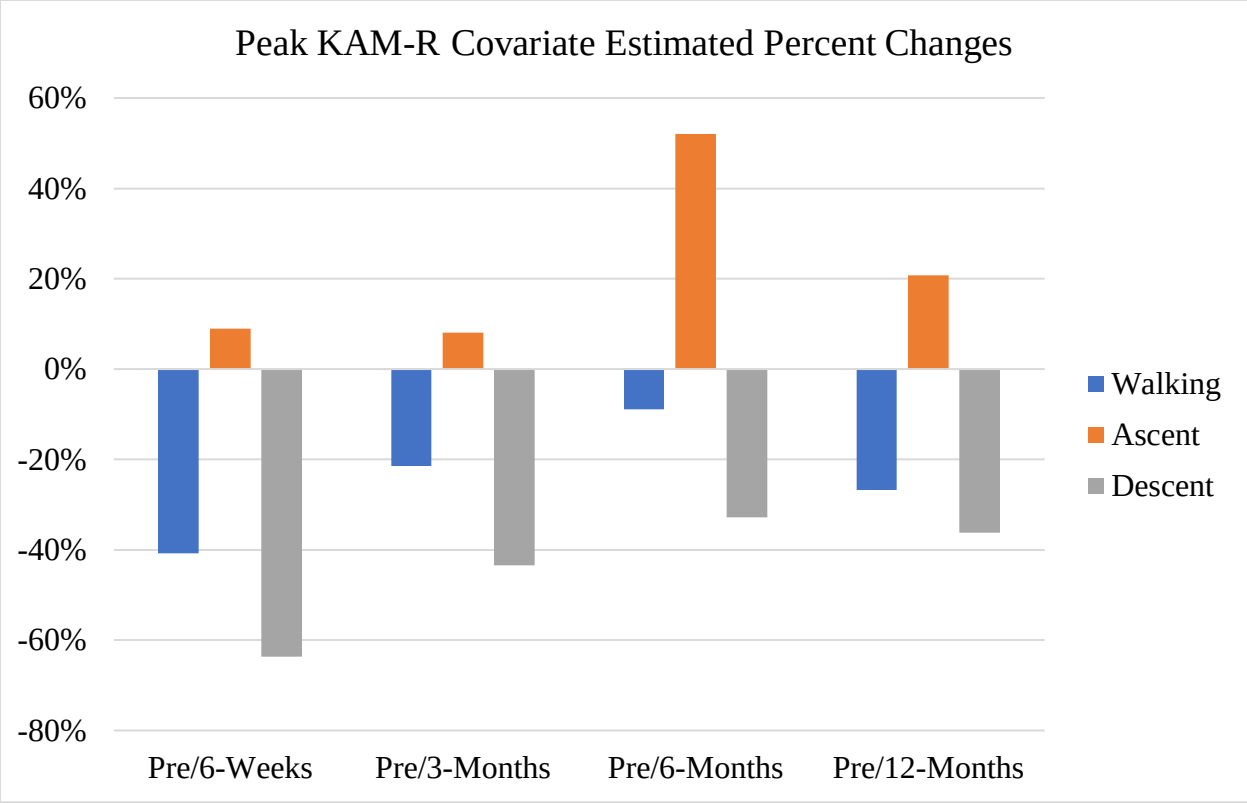

Figure 2. Illustrates peak KAM-R percent changes using ANCOVA estimated means during walking, stair ascent, and stair descent comparing from pre-TKA to each of the four post-TKA time points.

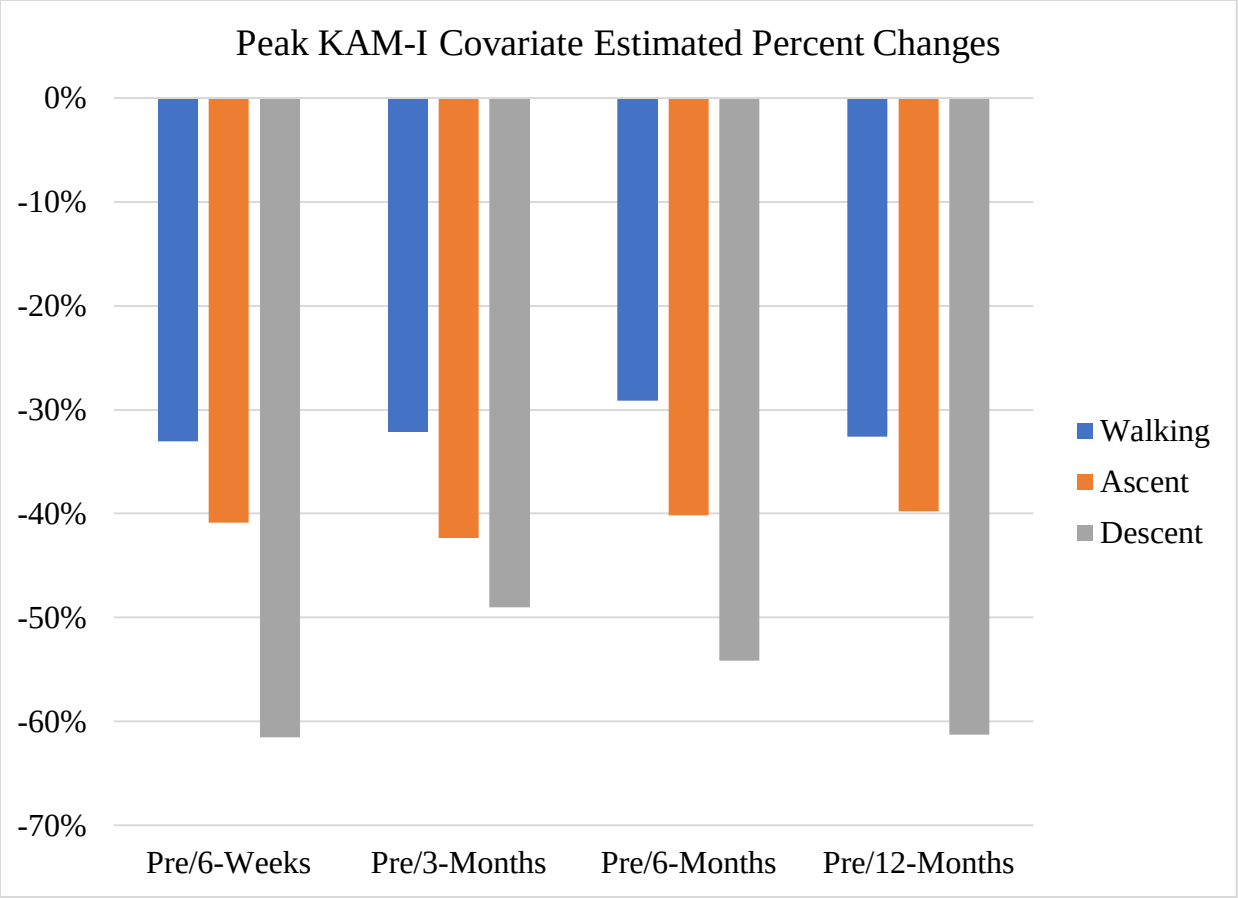

Figure 3. Illustrates peak KAM-I percent changes using ANCOVA estimated means during walking, stair ascent, and stair descent comparing from pre-TKA to each of the four post-TKA time points.

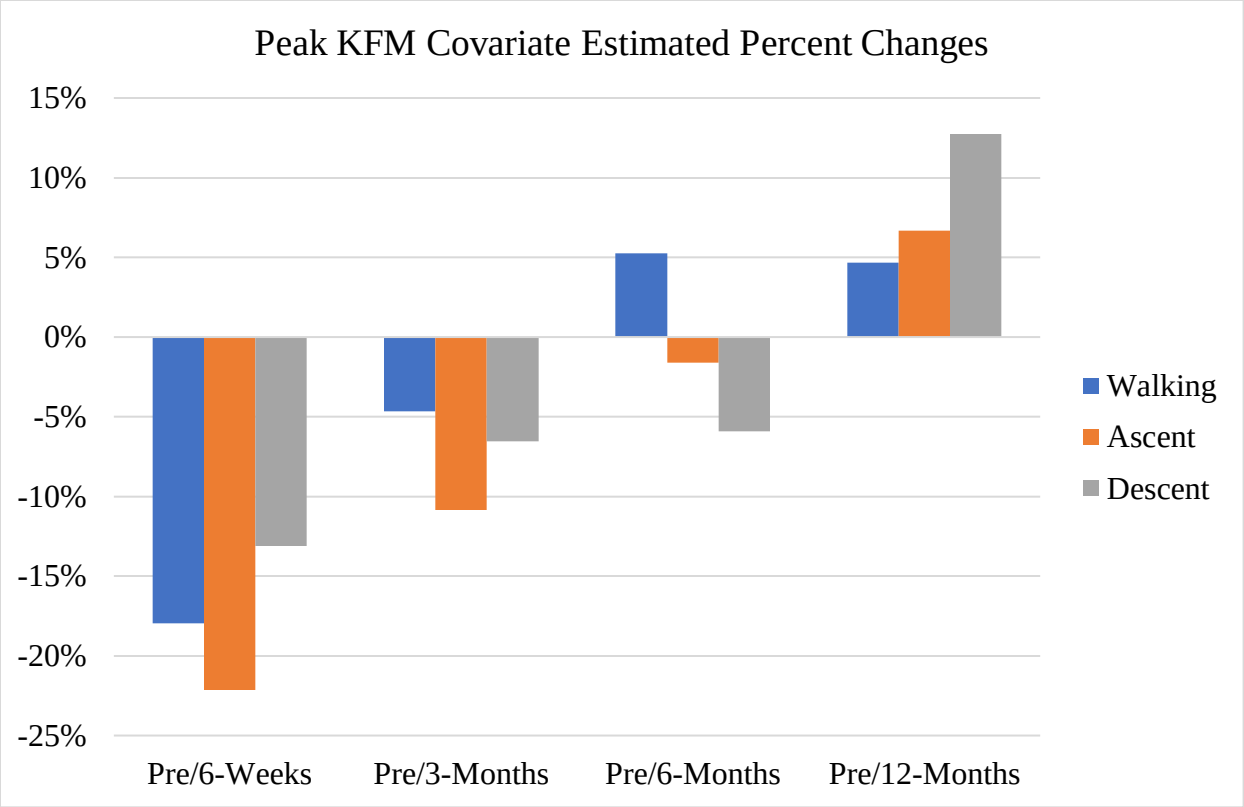

Figure 4. Illustrates peak KFM percent changes using ANCOVA estimated means during walking, stair ascent, and stair descent comparing from pre-TKA to each of the four post-TKA time points.

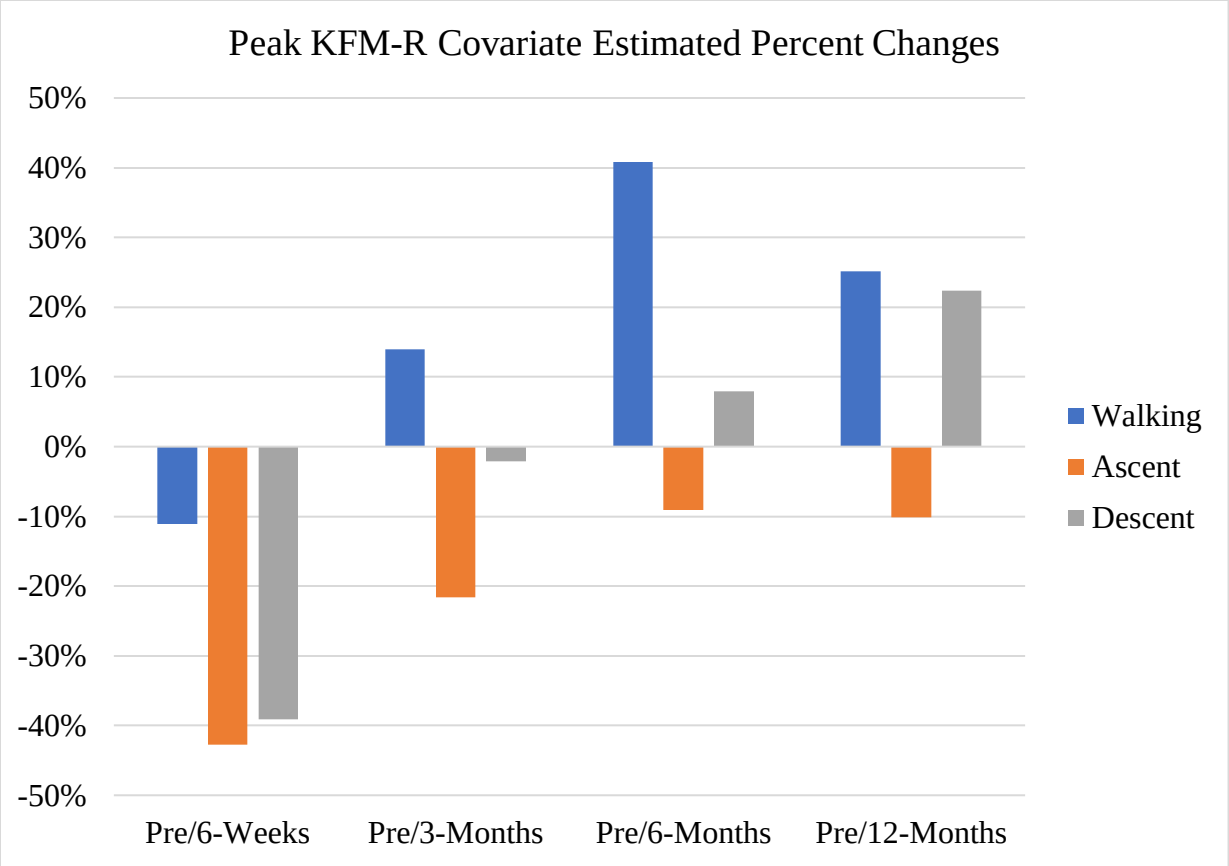

Figure 5. Illustrates peak KFM-R percent changes using ANCOVA estimated means during walking, stair ascent, and stair descent comparing from pre-TKA to each of the four post-TKA time points.

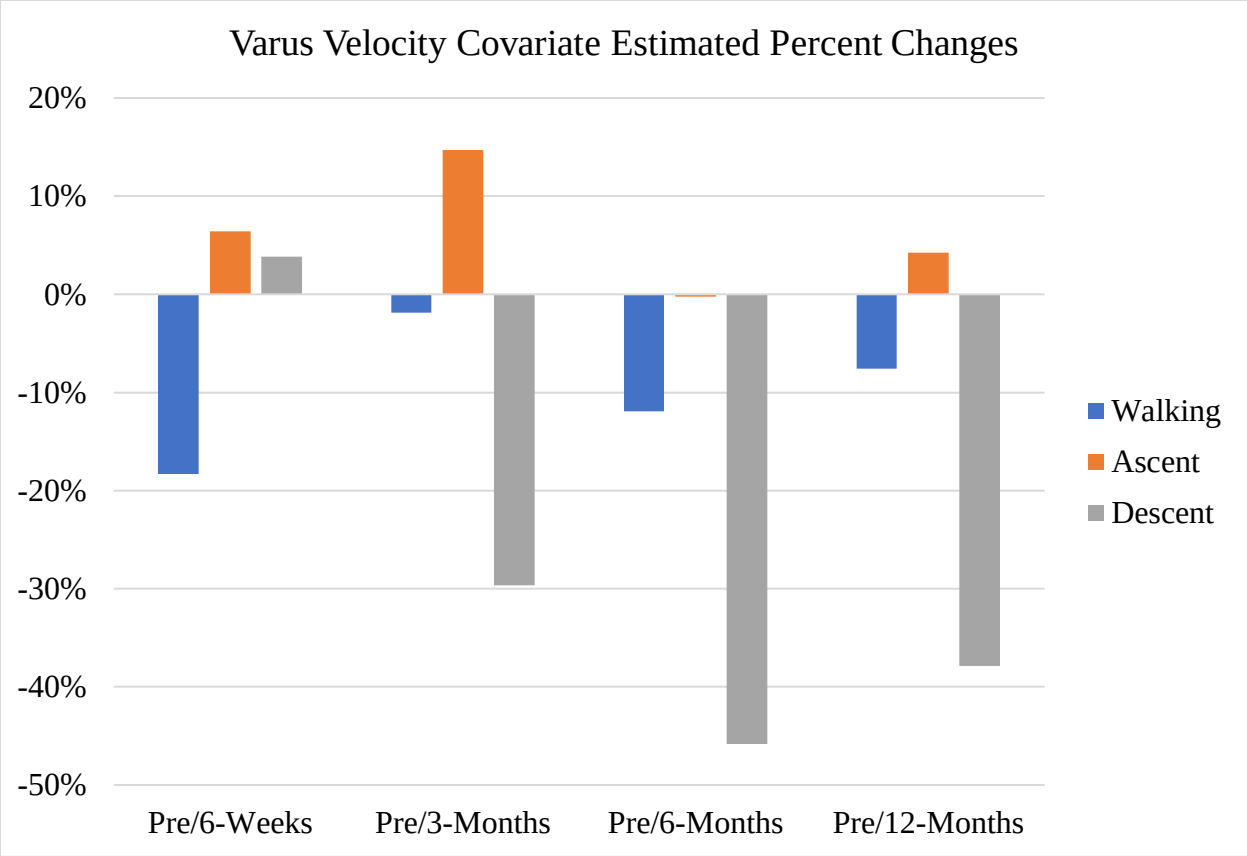

Figure 6. Illustrates varus velocity percent changes using ANCOVA estimated means during walking, stair ascent, and stair descent comparing from pre-TKA to each of the four post-TKA time points.

DISCUSSION

The most important finding of this study was that stair ascent and stair descent tasks provided additional insight, beyond walking, into the mechanical knee function of individuals with OA who underwent TKA. Figures 1-6 for biomechanical variables of interest indicate visual trends in percent change during stair ascent and stair descent that did not follow similar patterns to that of walking alone. Even when statistical and qualitative differences did not exist between modalities for biomechanical variables such as peak KAM and peak KAM-I, stair negotiation still provided beneficial information in discriminating between participants who demonstrated higher functional capabilities than their peers.

An additional finding of percent change analysis was that peak KFM and peak KFM-R experienced relatively linear increases from the 6-week comparison to the 12-month comparison, (Figures 4-5) showing an increase in willingness to load the knee. Increased KFM is expected and desired as participants continue regaining strength and confidence in surrounding musculature, ligaments, and tendons following TKA. In the current study, KFM percent change decreased during all modalities until the 6-month time period when walking demonstrated a positive percent change (Figure 4). By 12-months post-TKA, subjects demonstrated an increased KFM percent change in all three modalities once again suggesting a regained willingness to load the knee.

Initial decreases in KFM percent change, followed by continued positive trends may be explained by the weakness in surrounding soft tissues of the knee. Existing research suggests that following TKA, there is a time period in which participants need to retrain their gait and regain strength. One study reported significant differences three-months after TKA between limbs for those who underwent unilateral TKA with the surgical limb being weaker; however, three-years

after TKA, significant differences diminished.[24] The current study shows that by one-year post-TKA, participants have gained sufficient strength in their knee flexors as evidenced by a trending positive percent change for each modality at 12-months. It is unclear whether KFM and overall flexor and extensor strength continue increasing beyond one-year post-TKA or plateau.

Recent research from Doyle et al.[21] found KAM-R to be the most sensitive joint loading variable to assess knee-load related risk factors among other KAM variables. Previous research also found KAM-I to be more sensitive to changes in gait speed and mechanical joint loading than peak KAM alone.[25,26] While statistical sensitivity was not calculated in the current study, our results suggests that KAM-R is the KAM variable most likely to discriminate between the three modalities rather than peak KAM or KAM-I (Table 5). This finding is in conjunction with parallel investigation of Figure 2 where KAM-R percent change analysis of stair ascent provided unique mechanical insight into knee joint loading rate compared to walking or stair descent. Concurrently, KAM-I demonstrated similar percent change trends as peak KAM (figures 1 and 3) during walking and stair negotiation. Therefore, the results of our study provide support for using peak KAM-R rather than peak KAM alone (Figure 1) to discriminate severity of OA and prescreen participants who are at risk for OA progression and the need for TKA, particularly in stair negotiation tasks.

Correlations of Clinical ROM and Biomechanical Variables

The second main finding of this study was that KAM variables showed weak relationships between both pre-TKA and post-TKA clinical ROM in stair ascent and stair descent tasks. Research has cited peak KAM to be a risk factor in the development of OA[10] while KAM-R has been associated with medial tibiofemoral joint degeneration[22] and KAM-I has been identified as a possible risk factor for loss of medial tibial cartilage volume, a sign of OA onset.[17]

Despite KAM variables being well studied in level walking, to the author's knowledge, no research exists about KAM variables and stair negotiation.

With KAM variables accounting for the majority of significant pre-TKA ROM correlations (Tables 10-11), we confirm similar findings of previous research that KAM variables are associated with osteoarthritis of the knee.[10,15,17] While many studies associate KAM and knee OA, other research did not find associations between degenerative changes at the knee or structural damage and KAM-I.[17,22] However, previously mentioned KAM associations were all analyzed during level walking, not during stair negotiation as was this study. It appears that biomechanical variables at the 6-month and 12-month time periods compared to pre-TKA variables are more closely related to both pre-TKA and post-TKA clinical ROM (Tables 10-11). This is especially true for the three KAM variables. As ambulation modalities increased in difficulty, so did associations with clinical ROM—a unique finding of this study suggesting the need for more complex tasks to be performed to understand true function of the knee.

The greatest number of significant correlations between ROM and biomechanical variables of interest occurred during stair descent, followed by stair ascent, and walking. Correlation results suggest that select biomechanical variables and clinical ROM relationships are manifested most during stair descent, the task most difficult to perform for our subjects. Subjects were consistently able to complete the task of level walking more often than stair ascent, and the fewest were able to complete stair descent with no exception (Table 8). This agrees with previous stair research by McClelland et al. where more people in their study could perform stair ascent than stair descent.[27] Results indicate that mid-term (6-month) and long-term (12-month) biomechanical analysis of variables were more closely related to clinical ROM than

that of pre-TKA variables. This may be attributed to participants having less pain and being able to better retrain their gate, regain function, and regain more strength by those time periods.

Two seminal studies focusing on peak KAM reported an increase from the first post-TKA value to the final post-TKA value.[14,16] At three weeks post-TKA, Shimada et al. reported a peak KAM decrease of 30% while at 1-year post-TKA, there was only a 16% decrease.[16] Orishimo and colleagues in their research stated that presurgical levels of KAM may return as early as 1 year after TKA.[14] The current study confirms the findings of Shimada et al. that peak KAM increases from the first post-TKA time period to the 12-month time period. Conversely, results of the present study conflict with findings by Orishimo et al. that presurgical levels of KAM return by 12-months post-TKA (figure 7). As illustrated in Figure 7, peak KAM for each modality demonstrates a marked decrease from pre-TKA to 6-weeks, followed by mostly steady increases to the final three time points. While walking and stair ascent begin trending downward at 6-months, stair descent begins trending upward. Lower peak KAM values result in less loading in the medial compartment of the knee, an outcome desirable for both participants and clinicians for the lifecycle of a TKA.

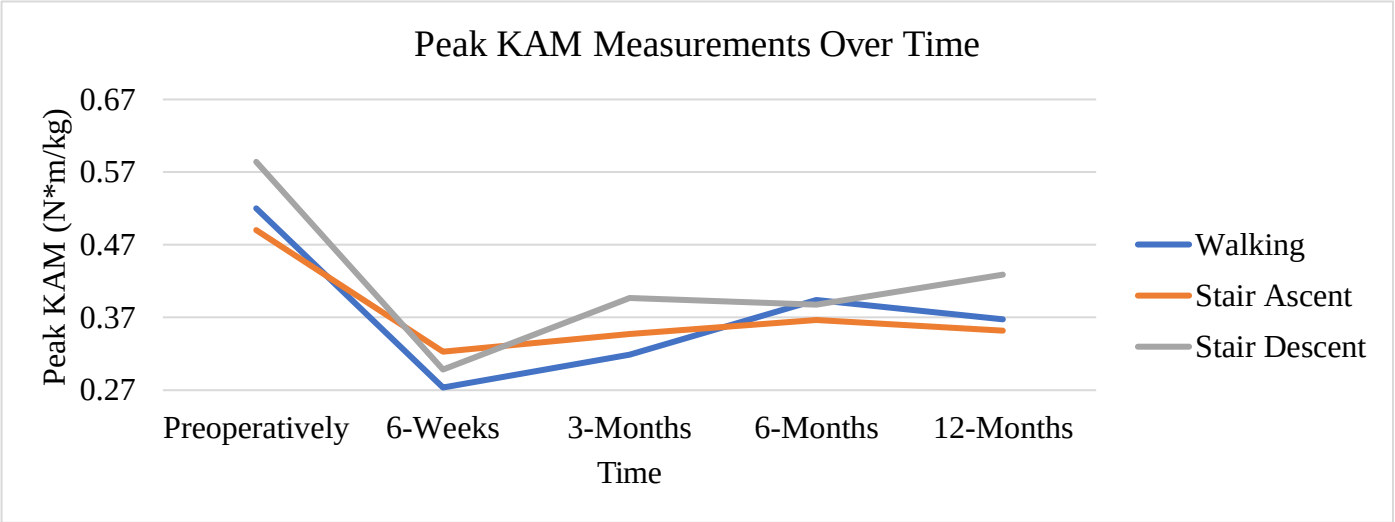

Figure 7. Peak KAM average values illustrated over time for the correlation time points and for 6-week and 3-month time points for each of the three modalities.

Interestingly, during walking, this study showed significant negative relationships between varus velocity at the 6-month and 12-month time periods (Tables 10-11). Previous literature has found that in varus aligned knees, varus thrust (velocity) increased the odds of OA progression 3-fold with varus thrust being a strong risk factor for medial knee OA progression.[28] One of the tenets of TKA is to realign the knee to 0° ± 3° of the mechanical axis.[29] For the subjects in our study, initial radiographical mechanical axis alignments were on average -5.9° with post-TKA radiographical alignments averaging -0.3°. Mechanical axis alignments with positive numbers are considered to be valgus and those with negative measures are varus.[30] These varus alignment differences likely accounted for a majority of the change seen from pre-TKA varus thrust values to post-TKA values resulting in significant correlations at the 6-month and 12-month-time periods during walking. Furthermore, varus velocity is largely dependent upon an individual's neuromuscular control. Pre-TKA, a majority of subjects likely lacked adequate neuromuscular control due to pain and weakness in and surrounding the knee joint.

ROM is of primary importance in stair descent where it is not possible to laterally trunk bend, hip hike, circumduct, vault, or use other compensatory mechanisms such as are possible during stair ascent. This is supported by correlation data where more significant relationships were seen during the stair descent task than during other modalities. The average peak knee flexion angle (PKFA) during walking in healthy young subjects is around 19°[31] while PKFA during stair ascent in healthy young subjects is reported to be 70° during the stance phase and 97° during the swing phase.[32] At the same time, PKFA during stair descent in the same population is on average 83° in the stance phase and 94° in the swing phase.[32] These kinematics provide valuable insight into why more relationships are not seen between passive clinical ROM and level walking. Level walking does not elicit enough ROM to see marked relationships. In the future, more appropriate insight into significant relationships may be gained by participants undergoing active ROM assessment since a valuable component of stair negotiation is neuromuscular control, better represented by active ROM.

Limitations

A number of limitations may have affected the findings of our study. First, there were numerous statistical outliers for biomechanical variables that may have skewed percent change averages, even after using the ANCOVA adjusted means. Second, sample sizes were not consistent across all modalities. At 6-weeks post-TKA, over half of the participants were unable to perform stair descent while over one-third were not capable of performing stair ascent. At 12-months post-TKA, just over half of the participants were capable of performing stair descent.

Furthermore, not all participants were present at each of the five data collection periods exacerbating the differences in sample sizes from one time period to the next. Rehabilitation for the participants and activity levels were not standardized which would have likely affected post-

TKA measurements of biomechanical variables. It is recommended that future longitudinal studies consider collecting data beyond one year while increasing the sample size to include enough participants to have an N of at least 25 for each modality.[33] These considerations would likely result in more complete and representative data giving a better idea of relationships amongst biomechanical variables and clinical ROM in addition to less standard deviation and standard error in between group comparisons.

One of the greatest limitations in correlation analysis was that ROM was not measured with a goniometer. Though, studies have shown less than a 5° difference between a visual ROM assessment and that of a goniometer.[34,35] Finally, for the ANCOVA analysis, there were numerous violations of Levene's test of homogeneity. It is unclear whether or not using a non-parametric test on non-normally distributed data is the best practice. Therefore, the authors accepted the results and continued with analysis.

CONCLUSION

The results of this study emphasize the value of both stair ascent and stair descent in analyzing knee mechanics of individuals with OA who later underwent TKA. Both stair ascent and stair descent provide valuable insight into the mechanics, overall health, and recovery of the knee following knee arthroplasty beyond that of walking analysis alone. Furthermore, stair negotiation proved to be an important measure to differentiate between the functionality and capabilities of participants over multiple time periods up to one-year post-TKA. Walking analysis alone may not provide enough difficulty for most subjects to elicit a complete understanding of knee function and joint loading mechanics. Correlation analysis revealed weak to moderate negative relationships between ROM and kinetic variables, especially during stair descent and at the 6-month and 12-month post-TKA time points. Relationships between

biomechanical variables and clinical ROM are manifested most during stair ascent and stair descent compared to walking. Interpretation of relationships with KAM should be carefully considered as the correlation strength was not sufficient to draw definitive conclusions. These data should be reviewed by clinicians in rehabilitation settings and consider that with decreases in ROM, kinetic variable outputs will generally increase, potentially predicting future risk for needing TKA or TKA revision. This negative relationship is desirable for all variables, except for KFM and KFM-R where a positive relationship is ideal. This study identifies stair ascent and stair descent as better means of understanding the relationships between clinical ROM and biomechanical variables for participants with OA who have undergone TKA.

REVIEW OF LITERATURE

Knee Osteoarthritis

In the simplest definition, OA is characterized by degeneration of the articular cartilage and subchondral bone. This often leads to pain, joint stiffness and disability.[36] Osteoarthritis is considered to be the most common joint disorder in the world where over 50% of people show signs of OA by the age of 65. By age 75, that number climbs to 80% of individuals showing signs of OA.[1] Additionally, knee osteoarthritis has been found to be the leading form of OA amongst all other types. In a study looking at 847 arthritic joints, 41.2% involved the knee indicating the need for research to be done to better understand the pathology of such OA.[2] In order to understand how OA is graded, radiographs of patients are taken and the Kellgren-Lawrence (K-L) scale is used.[37] The K-L scale uses ranges from 0 to 4 where 0 is no OA and 4 is severe OA. It is important to note that symptoms are not considered when judging the severity of OA. The 0 to 4 number is given based on the presence of osteophytes, periarticular ossicles, joint cartilage narrowing and sclerotic walls situated in the bone.[37]

According to Thomas et al.,[36] approximately 13 million adults 60 years old and up show signs of OA in radiographs with around 4 million of those showing symptoms of OA. For individuals who have sustained knee injury, they are 4.2 times more likely to develop OA than those who have not sustained knee injury.[38] This is a significant risk factor and predictor in whether or not someone will eventually experience knee OA. Additionally, genetic factors may account for 50% or more of the susceptibility of an individual to experience this degenerative disease. While physical activity to strengthen the musculature surrounding injured joints is typically recommended to improve function and decrease symptoms, this may actually increase OA because of repetitive use. This poses a public health concern as knee injuries are seen annually and there

seems to be a link between joint injury and OA development. Posttraumatic OA affects more than 5 million adults in the United States.[36]

While OA typically occurs over a single joint; particularly in early stages, it is not uncommon that changes in the function at one joint may lead to changes in function or an increase in disability in the contralateral joint.[39] In the end, Schmitt et al.[39] analyzed 20 knee OA patients after excluding 10 for incomplete data. Walking speed in a control group (1.38 ± 0.22 m/s $p < 0.001$) was found to be faster than that of the knee OA group to a significant degree. Interestingly, knee OA patients were seen to have a longer stance time (61.3% ± 0.6 % of cycle vs control of 60.5 ± 0.4) than that of the control group in this study. Along with that, subjects with knee OA were seen to have greater knee flexion in stance than the control with the addition of a greater peak knee flexion during the early stance phase. Notably, the presence of OA in the knee was found to have a global effect on gait and a lower initial GRF was seen compared to controls. This study only conducted analysis in the sagittal plane and did not account for kinetics in frontal or transverse planes. Schmitt's study supported other literature in that severe OA of a single joint alters not only the affected joint, but can potentially affect joint mechanics in other parts of the lower extremity.

In the introduction of Hicks-Little et al.,[3] they cite numerous sources indicating the importance of stair negotiation as an activity of daily living (ADL). The purpose of their study was to examine the effects of knee OA on hip, knee, and ankle joint kinematics variables during stair ascent and stair descent. For patients with early to moderate knee OA, their first complaint often comes from their difficulty in negotiating stairs. Knee OA has also shown in general a risk factor for falls in older adults; coupling this with ADL's including stairs increases the risk of falling. Hicks-Little et al.[3] found that their knee OA group demonstrated smaller peak knee flexion angle during the swing phase on both stair ascent (88.2° ± 6.7°) and descent (85.2° ± 4.1°). This is in

conjunction with a smaller average knee flexion angle at foot strike (57.8° ± 5.2°) compared to controls (61.5° ± 5.7°) and a smaller peak knee flexion angle during support (60.4° ± 5.0°) compared to controls (62.6° ± 5.4°) during ascent. Hicks-Little et al.[3] hypothesizes that this change is due to increased joint stiffness and pain. Also found in their study was a greater knee abduction during the swing phase in decent 6.4° ± 5.6°) compared to healthy controls (3.1° ± 3.6°). This is thought to result from a limit in knee flexion coupled with a more varus knee position to aid in negotiating the stairs. It was concluded that not only does knee OA directly affect knee joint kinematics during stair negotiation, but it also induces changes in the hip and ankle to compensate for changes at the knee joint.

Total Knee Arthroplasty

Patient satisfaction is a typical outcome measure following TKA, often measured through patient pain and function assessments among others.[40] Bourne et al.[40] found from a cross-sectional study of patient satisfaction after 1703 TKAs performed in the province of Ontario, Canada, approximately one in five (19%) of all patients were not satisfied with the outcome. This meant that the patients were in one of three categories: neutral, dissatisfied or very dissatisfied. Bourne et al.[40] found that the strongest predictors of patient dissatisfaction after primary TKA were expectations not being met (10.79 greater risk), a low 1-year WOMAC score (2.59 greater risk), preoperative pain at rest (2.49 greater risk) and a postoperative complication requiring hospital readmission (1.99 greater risk). Evidently there is a well-documented discrepancy between clinician and patient ratings of health status.[41] Regarding patient function, patients were least satisfied in getting in or out of a bus/car with 30% being unsatisfied and 27% being unsatisfied while ascending stairs. Bourne found, along with Noble et al.[42] that patient dissatisfaction

decreases with advancing age, residual symptoms, expectations not being met and less functional improvement. This is significant in regards to this study because the mean age was 70 ± 9 years.

In order to decrease pain and limitations during activities of daily living, knee arthroplasty has grown in procedure for individuals with knee OA.[4] Evidence suggests that total knee arthroplasty increased in volume 161.5% from 1991 to 2010. Available data suggests that 600,000 TKA procedures are performed in the United States each year costing approximately $15,000 per procedure making it a $9 billion industry.[4] Additionally, TKA demand is expected to grow to nearly 3.5 million procedures by 2030 which includes revisions for patients with previous TKA procedures.[5] Total knee arthroplasties are being used to restore form and function to individuals who experience disability due to the degeneration of joint cartilage.

Thus, the primary objective of the Cram et al.[4] study was to evaluate longitudinal trends in primary and revision TKA volume, per capita utilization, and outcomes in the US Medicare population. Their research showed that TKA procedures grew from just under 100,000 per year in 1991 to nearly 250,000 in 2010. In addition, the number of TKA revisions doubled from around 10,000 in 1991 to around 20,000 in 2010. At this time, these numbers are not predicted to decrease as suggested by predictions made by.[5] This increase is TKA volume can be attributed to an increasing number of Medicare enrollees and in per capita realization according to.[4] For primary TKA, length of stay in the hospital decreased from 7.9 days in 1991-1994 down to 3.5 days in 2007-2010. These decreases in length of stay manifested themselves in the future corresponding to increases in hospital readmission rates. During the nearly two-decade time span from 1991-2010, the per capita utilization of primary TKA increased by 99.2% and the per capita utilization of revision TKA increased by 56.8%. Despite the growth in TKA procedure, it is unknown whether

or not all of the operations being performed are completely appropriate because the United States lacks a national joint arthroplasty registry.

In a study by Hatfield et al.[7], they found that changes between pre TKA and post TKA were towards an asymptomatic pattern and included improvements in motion, function and loading at the knee. In this study, sixty patients with severe knee OA visited a laboratory for gait testing approximately 1 week before TKA surgery. Subsequently, patients revisited the facility 1 year after the TKA. All participating patients had Kellgren-Lawrence scores of 3 or 4, indicative of severe OA joint changes. Following TKA, patients were found to have lower KAM's during the stance phase of gait which were statistically significant. Also, patients had a significantly greater difference between the first peak and midstance knee adduction moment than they did preoperatively. Notably, loading was decreased in the medial compartment during gait after TKA; however, walking velocity increased post-TKA and the magnitude of the peak KAM during early stance has previously been shown to increase with walking velocity.[20] An important finding of Hatfield et al. is that the change in hip-knee-ankle angle explained 30% of the variance in the change in overall magnitude of the KAM.

Knee Adduction Moment

Knee adduction moment variables are considered to be potential indicators in the onset of knee OA and also predictors for needing a TKA or TKA revision.[10] Many studies have analyzed gait biomechanics during ambulation and knee adduction moment has become increasingly relevant.[7,9,11–16] Despite the fact that peak KAM only represents loading at a singular moment in time, it is also known to be a surrogate for loading in the medial compartment of the knee.[10] Originally, KAM variables were thought to decrease after TKA and remain low, a desired outcome for both medical professionals and clinicians. At this time, there is a disconnect in literature

indicating that high KAM variables, specifically KAM impulse may be a risk factor for loss of medial tibial cartilage volume, a sign of OA onset.[17]

Relevant data showing how peak KAM changes over time is important to understand the effectiveness of TKA and implications for the future. This is particularly true for how peak KAM changes from the pre-TKA measurements to the final data collection in each study. Two studies found reported an increase in peak KAM from the first postoperative value to the final postoperative value.[14,16] At three weeks postoperatively, Shimada et al.[16] reported a peak KAM decrease of 30% while at the 1-year mark there was only a 16% decrease. This reduction at 1-year proved not to be statistically significant whereas the reductions at 3 weeks, 3 months and 6 months were statistically significant.[16] Orishimo et al.[14] in their research stated that presurgical levels of KAM may return as early as 1 year after TKA.[14] This is evidenced in his reporting that peak KAM was reduced to 85% of the preoperative level at 6 months while increasing to 94% of the preoperative level at 1 year.[16] At the same time, a study with unilateral TKA reported a 12% increase in KAM for the contralateral side not receiving TKA which was unexpected.[15] Under normal conditions, if the contralateral side did not have osteoarthritis, one should expect no change from pre-TKA to post-TKA. Some suggest that deviation of the tibial component from neutral mechanical alignment has been considered a risk factor for asceptic loosening—a result of imbalanced load distribution between both the medial and lateral compartments.[13] Along with this, varus component alignment has been considered to increase external KAM which will put patients at risk for loosening of the tibial component.[13]

A critical piece of research analyzing the frontal plane variable of KAM comes from[14] as aforementioned. This study performed gait analysis on 15 patients with 17 TKAs before surgery, 6 months post-TKA and 1 year post-TKA where the mean age was 65 years (range, 56-70 years).

Interestingly, Orishimo et al.[14] found that in the braking phase, knee adduction moment was reduced to 85% of preoperative levels at 6 months ($p = 0.037$), but increased to 94% of preoperative levels at 1 year ($p = 0.539$ versus preoperative). This team recommended further longitudinal studies to be done in order to see the definitive results of TKA in at the 1 year and beyond time frame. Orishimo et al.[14] concluded that TKA initally corrects for excessive peak KAM and KAM impulse; but, it is unknown how long this correction stays and if improvements are seen in clinical measurements such as static aligment and Knee Society (KS) scores/function scores. Orishimo et al.[14] addressed the unliklihood of the increase in peak KAM from 6 months to 1 year and found it unlikely to be due to an increase in gait velocity. This is in conjunction with Robbins and Maly who found a 7% increase in peak KAM with a 15% increase in gait velocity.[25] Orishimo et al.[14] also found increases in KS scores and KS function scores 6 months post-TKA and further improvement after 1 year.

Ro et al.[15] recruited 23 patients with advanced unilateral knee OA to collect data pre-TKA and two years post-TKA. Two years post-TKA, the K-L grade in the contralateral knee was worse in 25% of the patients. While peak KAM was found to decrease in the operated knee after two years, it had a statistically significant increase in the non-operated knee. At the same time, peak KFM showed no significant change in both knees. A multiple regression analysis revealed that the change in KAM from baseline to two years was best predicted by the baseline mechanical axis of the non-operated knee. Ro et al.[15] found that if the baseline mechanical axis was four degrees varus or above, the peak KAM at two years increased by 0.64 (% bodyweight*height). However, for varus less than four degrees, it was unchanged. This was the most significant finding of their study since a varus deformity four degrees or above in the non-operated knee was likely to develop pain, increased KAM and advance in knee arthritis. This studied mentioned how Nishimura et al.[43]

observed that 49.2% of patients with unilateral knee OA developed knee OA in the contralateral knee in 5.3 years on average. A final important finding of this study was that there was asymmetry of the mechanical axis between the non-operated and operated knees. These may result in subclinical varus thrust and may be associated with increased joint loading. Ro et al.[15] found that patients with unilateral advanced OA had asymmetrical gait patterns that became more symmetrical after unilateral TKA.

A 2016 study by Stickley et al.[30] published in 2017 considered the use of standard radiographs and measured tibiofemoral angle (TFA) to assess alignment in the lower extremity, specifically the knees. Data for the mechanical axis (MA) was taken from hip-to-ankle radiographs and TFA and femoral angle were measured on standard radiographs from 788 cases of diagnosed knee OA. Stickley and colleagues created regression equations for males and females capable of predicting MA and TFA such as what is measured on standard radiographs. This study defined varus as being a negative measurement on the knee's MA while valgus was positive. Stickley et al. concluded that current methods used for predicting MA from TFA was not sufficient for estimating MA within ± 3° for roughly one-third of OA patients before undergoing TKA.

In 1991, Jeffery et al. looked at frontal plane alignment after total knee replacements (TKR). From this study, they determined that one of the tenets of TKA is to realign the knee to 0° ± 3° of the mechanical axis. Over a period of five years, the study took 139 Denham TKR from operations performed at Queen Alexandra Hospital, Portsmouth. The study included 102 patients and 115 replacements. Before performing the TKR, Maquet's line passed through the middle third of knees only 13% of the time in the 115 radiographs taken. After TKR, this was the case in 68% of the early radiographs and 65% of those taken eight years after the initial TKR. Maquet's line passes form the center of the femoral head to the center of the body of the talus. Over time, 10%

of the knees were revised for loosening or for showing signs of loosening. This study states that a normal tibiofemoral angle is 7° valgus and Maquet's line corresponds to 3° from that normal angle.

Knee Adduction Moment Impulse

While reported less frequently than peak KAM, knee adduction moment impulse has grown in reporting in recent years.[9,12,14,21,22] KAM impulse incorportates both the magnitude and duration of the KAM which may merit more consideration as it gives an idea of total exposure rather than a single snapshot in time. KAM impulse can be defined as the net positive impulse of the KAM curve according to Doyle et al.[21] This time related varaible has also been identified to being a possible risk factor for loss of medial tibial cartilage volume which is a sign of osteoarthritis onset[17] and was more sensitive for discriminating between OA severity than KAM peak measurements.[26] In three recent studies, Debbie et al.[12] saw a 27% decrease, Orishimo et al.[14] a 35% decrease and Paterson et al.[9] found a 48% decrease for men with a 22% decrease for women.[9,12,14] These findings were all statistically significant and showed similar outcomes to the peak KAM measurements.

Robbins et al.[25] considered KAM impulse in a study of 32 healthy participatns with 18 women being recruited. The data was collected over three ambulation speeds: self-selcted, slow and fast. The slow and fast paces were 15% slower and faster, respectively than their self-selected pace. Analysis of the data included a one-way repeated measures ANOVA. The purpose of this study was to examine changes in peak KAM and KAM impulse in response to controlled changes in gait speed in healthy participants during level ambulation. Robbins and Maly[25] found that KAM impulse measured in N*m*s at the self-selected speed was significantly lower than that of a slow speed (8.97 ± 3.88 vs 10.07 ± 4.69). There was no significant difference found between the self-selected speed and the fast speed (8.97 ± 3.88 vs 8.69 ± 3.93). Peak KAM measured in N*m saw the highest value at the fast speed (32.28 ± 13.18), the lowest at the slow speed (27.63 ± 10.08)

and the self-selected speed at 30.05 ± 10.97 in the middle. KAM impulse proved to be more sensitive to changes in gait speed than peak KAM since a decrease of 15% in speed resulted in a significant increase in KAM impulse. For peak KAM, significant differences were only found between the slow and fast walking speeds, representing a 30% difference in gait speed. Concluding, since peak KAM and KAM impulse saw changes in opposite directions, it is suggested than the variables represent different characteristics of medial knee loading. Additionally, slowed gait speeds increase loading exposure on the medial knee tissues as evidenced by the KAM impulse data.

In a study by Debbi et al.[12], they studied fifty patients with end-stage knee OA pre-TKA and six weeks post-TKA. Patients underwent a gait analysis, completed a Time-Up-Go test, a Six-Minute-Walk test and a WOMAC questionnaire. Debbi et al.[12] found that first and second peak KAM decreased to 74% and 79% of preoperative levles while KAM impulse decerased to 73% of its pre-TKA level. KAM impulse was reported in percent bodyweight*height*gait cycle. The values pre-TKA in the operated knee were 120.14 ± 58.89, 88.18 ± 42.55 post-TKA, 128.24 ± 51.61 pre-TKA in the non-operated knee and 122.75 ± 48.62 post-TKA in the non-operated knee. Notably, between the pre-TKA and post-TKA values in the non-operated knee, KAM impulse did not change while peak one of KAM even decreased.

Expanding on the Orishimo et al.[14] study in the KAM section, they found that KAM impulse during the braking phase decreased from pre-TKA to six months post-TKA but then saw a rise at the 1-year mark. Though, that level was still lower than the preoperative measurement. In the propulsive phase, the KAM impulse decreased at six months and remained low at 1-year. Orishimo et al.[14] did not find any correlations between changes in peak KAM and KAM impulse and changes in clinical scores with time. It was concluded that despite TKA initially correcting

excessive KAM and KAM impulse, it is unclear whether or how long the correction will persist and if improvements in these kinetic measurements are associated with changes in clinical measurements.

Morgenroth et al.[22] who are expanded upon in the moment rate section also briefly reported KAM impulse data. Their calculations were done using the trapezoid rule without normalizing stride time in a custom written MATLAB program. Degenerative changes at the knee were not found to be associated with KAM impulse which was consistent with a finding by Bennell et al.[17] showing a lack of association between KAM impulse with signs of structural damage such as medial tibial cartilage defects or bone marrow lesions. Morgenroth et al.[22] acknowledged that type II error may have resulted in a lack of statistical relationship to KAM impulse since they had a small sample size.

Paterson et al.[9] who are expanded more upon in the KFM section briefly studied KAM impulse in N*m*s as the positive area under the KAM-time graph for the entire stance phase. From pre-TKA to post-TKA, KAM impulse saw a decrease of -8.5 N*m*s. This study demonstrated how sex, but not obesity influenced changes in KAM impulse. There was a significant reduction in KAM impulse for men while women did not show changes post-TKA. However, Paterson et al.[9] found in previous work[44] that men have higher KAM values compared to women pre-operatively which may give them a greater likelihood of seeing kinetic reductions post-operatively.

Knee Flexion Moment

Knee flexion moment (KFM) has been a kinetic variable of interest to researchers since an increase in KFM in early stance phase, coupled with an increase in late stance knee extension moment indicate improved attentuation and function at the knee.[7] The KFM has often been considered in OA and TKA research as a key indicator of overall health, functionality and recovery

of the knee pre and post-TKA.[7–9] A high knee flexion moment has been shown to be indirectly related to qualitative quality of living scores since an increase in KFM may show improved confidence in knee joint in knee joint function, reduced muscle pain and potentially improved muscle strength.[8]

In a five year longitudinal study performed by Chehab et al.[10] with 16 subjects with medial knee OA, they used multiple regression to determine whether baselines measures of KAM and KFM were associated with cartilage changes over those five years. Chehab et al.[10] basis behind this research was that current interventions (2014) were aimed at reducing joint laods by focusing only on the KAM. Chehab et al.[10] found that the unstandardized univariate regression showed that a 1% BW*Ht increase in the baseline KFM indicated an average reduction of 0.06 units in the tibial medial to lateral cartilage thickness ratio over 5 years. The R^2 value of this was 0.40 with a p-value of 0.009. Chehab et al.[10] found that KFM was significantly correlated with changes in the tibial medial central, tibial medial posterior, tibial medial internal and tibial medial anterior regions over 5 years. Of significance was the finding that KFM is related to changes in medial-to-lateral thickness distribution since this load can change when interventions are introduced. The results show that decreasing KAM while inadvertently increasing KFM may be detrimental to cartilage health in certain regions of the knee.

In a study by Hatfield et al.[7] consisting of 42 patients with OA, data was collected 1 week pre-TKA and 1-year post-TKA. All patients participating in the study had Kellgren-Lawrence scores of 3 or 4. Additionally, all subjects had medial compartment involvement with 33 being predominantly medial knee OA and 9 equally affected in medial and lateral compartments. Increases in the knee flexion moment early stance were found in conjunction with late stance knee extension moment increases, the combination of which indicate improved impact reduction and

function. Hatfield et al.[7] use a term called principal components (PCs) where the PCs capture the major amplitude and shape characteristics of the original waveform data and scores indicate how much a PC contributed to each original measured waveform. For KFM, a significant difference was found in PC2 which was a flexion/extension moment difference from pre-TKA to post-TKA. The PC2 pre-TKA score was 1.37 and 1.84 post-TKA. Hatfield et al. draw the conclusion that impact reduction is seen during early stance since the flexion moment increases during early stance. At the same time, they say improved function is indicated by an increase in extension moment during late stance phase. Their results showed that patients had more bimodal flexion moment waveforms. Concluding, changes in knee joint motion and joint loading were found for the dynamic KFM measured during walking after TKA surgery.

In a study by Landry et al.[20] of 41 subjects with moderate knee OA and a 43 subject control group, they collected data on knee abduction/adduction moments, flexion/extension moments, internal/external rotation moments and flexion/extension angles. Data were collected at a self-selected walking pace (SSWP) and 150% of that pace. This study aimed to compare knee joint angle and moment waveform patterns between mid-to-moderate OA patients and control subjects using principal component analysis (PCA). Notably, five participants had a K-L score of 1, 22 had a score of 2 and 14 had a score of 3 in addition to OA patients being older and heavier on average. In this study, the first two PCs for the flexion/extension moment waveforms captured group and speed differences in early stance and speed differences throughout stance. Unsurprisingly, OA patients had smaller KFM magnitudes during stance phase than that of the control subjects at both speeds while both groups had higher KFM's at 150% of the SSWP. PC2 indicated no difference between the two groups capturing no significant overall amplitude difference. [19] found that smaller KFM/s were reported in OA patients which has been associated with quadriceps or pain avoidance

gait. Concluding, this study characterized gait in a moderate knee OA population at a SSWP and 150% of that pace. PCA detected changes from controls in the shape of the gait waveforms that was not previously identified with other analysis techniques.

Kaufman et al.[19] studied knee kinematics and kinetics in 139 patients with Grade 2 knee OA during level ambulation, stair ascent and stair descent. This group of OA subjects had an age range from 30 to 82 years old (mean of 57 years) and a healthy control population of 20 subjects ranging from 20 to 42 years old (mean of 30 years). Kaufman et al.[19] did not find a significant KFM or rotational moment difference between the OA and control groups. While there were no statistically significant differences in KFM between the two groups and between male and females, there was a difference in knee flexion. Females had knee flexion angles that were significantly higher than that of the males for the subjects with OA. This is true for level walking and stair ascent/descent. Kaufman et al.[19] concluded that the difference in KFM may be attributed to a height difference between the male and females. The researchers also concluded that the subjects attempted to minimize their pain by reducing the knee extensor moment which represents the intent by the subjects to reduce their pain by minimizing knee joint loading. The sagittal plane knee moments in this study proved to be smaller in magnitude than previous reports during stair ascent while being similar during stair descent. Of significance is the acknowledgement than moments reported in this study are somewhat lower to other studies due to a difference in step height (18-cm high stairs with a 25 cm run).

Level Ambulation and Stair Ambulation

The ability to negotiate stairs through ascent and descent is needed for many as an ADL as stairs, if not in homes provide convenient access points to buildings and community services.[27] Bourne et al.[40] found that patients were least functionally satisfied by their ability to

get out of a bus or car (30% dissatisfaction) and 27% being dissatisfied during stair ascent. A study by Costigan et al.[18] stated that for patients with early to moderate knee OA, their first complaint was often difficulty with stair ascent. Many studies have looked at knee kinetics and kinematics following TKA during level ambulation; fewer have studied the same during stair negotiation alone and even fewer have looked at the two in the same study. A systematic review by Standifird et al. explored the biomechanical adaptations during stair ambulation that occur after TKA where they included 13 studies in the review. Standifird et al.[45] found that during stair ascent, TKA patients showed reductions in knee flexion angle at contact, maximum knee flexion, total knee flexion ROM and ascent velocity compared to healthy controls. Standifird et al.[45] found mixed results in joint moments during stair descent suggesting that TKA patients either recovered or results were confounded by other unaccounted factors. Two factors that may lead to these discrepancies in joint moments are patient recovery and walking speed.

McClelland et al.[27] studied 40 patients with a modern TKA prosthesis and compared them to 40 matched control participants during stair ascent and descent. Notable from this study is that only 33 control participants and 26 TKA participants could complete stair ascent independently after several attempts. 33 control participants and 21 TKA participants were able to complete stair descent independently. McClelland et al.[27] broke down their TKA group into a "normal" cluster called Cluster 1 and an abnormal cluster, Cluster 2 who showed more standard KFM curves. During stair ascent, the control group saw a maximum knee flexion moment during loading of 3.8% of bodyweight*height (Bw*Ht) whereas most of the Cluster 1 group saw a maximum knee flexion moment during loading of 2.7% of Bw*Ht. During stair descent, the control group saw a maximum knee flexion moment during loading of 3.2% of Bw*Ht whereas most of the Cluster 1 group a maximum knee flexion moment during loading of 2.6% of Bw*Ht.

A statistically significant difference was only detected in the stair ascent trials between the two groups. No significant differences were reported during stair ascent or stair descent comparing unilateral and bilateral TKA patients and their knee flexion moments during loading. This was the first study to report two distinct patterns of sagittal plane knee moments during stair descent. One in five of the TKA patients (Cluster 2) seemed to avoid generating a KFM, evidenced by a reduction in the magnitude of the KFM and a premature change to a KEM.

Bjerke et al.[46] performed a cross-sectional study on 23 unilateral TKA subjects at approximately 19 months post-TKA alongside a 23 subject control group during stair ascent. This study used EMG and assessed knee muscle strength by maximal voluntary concentric contractions, and whole-body kinematics and root mean square (RMS) electromyography (EMG) of the vastus lateralis and semitendinosus. Bjerke et al.[46] found quadriceps peak torque on the TKA side to be significantly lower compared to the contralateral side (prosthesis side: 1.24 N*m/BW ± 0.40 and contralateral side: 1.67 N*m/BW ± 0.43). The stronger, contralateral side still yielded a lower peak torque than the control group average, though (contralateral side: 1.67 N*m/BW ± 0.43 and control average: 2.07 N*m/BW ± 0.33). The hamstring strength of the TKA side was significantly lower than the average of both sides in the control group (prosthesis side: 0.92 N*m/BW ± 0.29 and control average: 1.11 N*m/BW ± 0.21). However, the contralateral side produced a hamstring strength equal to the average of the control group sides. Concluding, the quadriceps strength was 40% lower in the prosthetic side and 20% lower in the contralateral side compared to controls. Despite the TKA side being significantly weaker than the contralateral side, the relative effort in stair ascent was similar between the sides. Bjerke et al.[46] rejected their hypothesis that there would be a compensatory strategy in order to reduce the load on the prosthetic knee with an increased forward trunk lean in the TKA group compared to the control group.

Hicks-Little et al.[3] studied 18 subjects with knee OA with an average age of 60.2 years and 18 healthy matched controls with an average age of 60.3 years. The purpose of their study was to compare various hip, knee, and ankle joint kinematic variables between knee OA subjects and matched healthy controls during stair ascent and descent. This study found that knee OA and control subjects demonstrated greater hip flexion angle at foot strike and ankle dorsiflexion angle during swing while showing smaller ankle dorsiflexion angle during support during stair ascent compared with descent. The knee OA subjects also demonstrated smaller peak knee flexion during support (60.4° ± 5.0°) and swing (86.7° ± 5.4°) compared to the controls. While considering frontal plane motion at the hip, the OA group showed a greater hip abduction angle at initial contact (3.1° ± 3.9°) compared to healthy subjects (-0.5° ± 4.9°). This difference may be a result of knee OA subjects raising/lowering their leg onto the next step without having to increase the amount of knee joint flexion. Hicks-Little et al.[3] suggested that knee OA subjects also decreased the amount of knee flexion compared to controls during foot strike, support, and swing as a result of increased joint stiffness and pain. Hicks-Little et al. found no differences in this study between the knee OA and healthy groups on average hip flexion angle at foot strike during both stair ascent and stair descent. Finally, knee OA and healthy groups demonstrated greater average hip flexion angle at foot strike (OA = 57.4° ± 7.9°, healthy 61.6° ± 9.3°); during stair ascent compared with that during stair descent (OA = 14.8° ± 10.1°, healthy 15.4° ± 9.0°). This is logical as a greater amount of hip flexion is required during ascent in order to clear the step than is required in stair descent. Concluding, the data found in this study demonstrated that knee OA directly influences certain knee joint kinematics while inducing kinematic alterations at the hip and ankle. This is thought to occur in order to compensate for knee OA.

Varus Velocity/Thrust

Little is known of varus thrust/velocity at this time as the literature exploring such is limited while there are discrepancies in the definition. Some of the first studies on varus thrust suggest that data can be collected simply observationally and that it can be defined as a rapid, abrupt onset of varus alignment.[28] Overtime, that definition has changed as some have reported varus thrust in degrees.[47] After that convention, Chang et al.[48] suggested that angular velocity may be a better suited indicator. Stickley et al.[49] used varus thrust and varus velocity interchangeably so as to allude to the foundational work of Chang et al. while reporting varus velocities in °/s. Varus thrust has been previously reported as an indicator of progression and severity of knee OA.[28] Varus thrust was defined by Chang et al as the ‘‘dynamic worsening or abrupt onset of varus alignment as the limb accepts weight,’’ despite their initial examinations being qualitative in nature through aforementioned observation.[28]

Chang et al.[28] conducted a study with 237 patients with knee OA to assess varus thrust. 64 of those patients also underwent gait analysis to determine maximum KAM. Varus thrust was found to be present in 67/401 knees. They found that in varus aligned knees, thrust increased the odds of OA progression 3-fold while having thrust in both knees versus neither was associated with a 2-fold increase. This study stated that varus thrust was a strong risk factor for medial knee OA progression identified through simple gait observation. Also found was that varus thrust increased the likelihood of progression among varus aligned knees considered separately. This suggested that knees with a thrust were a subset of varus-aligned knees at particularly high risk for progression of OA.

Chang et al.[48] conducted a second study on varus thrust further expanding to consider varus thrust in the context of angular velocity rather than solely observationally. This study involved 236 people contributing 440 knees to the study where 82 were found to have definite varus thrust. In

the analyses of Chang et al.[48], varus was defined as 178° or less, valgus as 182° or greater and neutral as 178°–182°. During level ambulation, knees with observationally defined varus thrust on average had 7°/s faster varus angular velocity than those without varus thrust. It is noted the importance of measuring knee varus angular velocity since it embodies not only direction but also speed of motion. On the contrary, varus thrust (in Chang et al.[48] context) only reveals position of the knee at one instant of time and does not capture the dynamic movement seen in varus thrust. The average peak knee varus angular velocity was reported to be 26.81°/s in all knees, 32.23°/s in knees with varus thrust and 25.57°/s in knees without varus thrust. Concluding, visualized varus thrust during walking was associated with a greater peak knee varus angular velocity along with a greater peak knee varus angle during the stance phase of gait.

Farrokhi et al.[50] conducted a study considering varus and valgus motion related to muscle strength in patients with knee OA. There were eleven participants assessed radiographically as having medial compartment knee OA at a K-L grade of level 2 or higher. Included was also a healthy control group of eleven subjects. Patients with knee OA were found to have greater knee varus motion excursions compared to the control group. Specifically, the control group saw 1.0° ± 0.3° of varus motion excursion while the knee OA group saw 1.8° ± 1.3° (p-value < 0.01). Revealed through correlation analysis were non-significant linear associations between varus motion excursion with medial and lateral compartment joint contact point excursions/velocities in the control group. Findings from this study suggest that patients with knee OA move through greater degrees of knee varus motion excursion during the loading response phase of downhill gait compared to the control group. It is likely to see greater symptoms of knee OA and further joint damage from activities of daily living due to varus excursions in patients with knee OA because of more rapid medial/lateral translations of the joint contact points and magnitude of contact forces.

Concluding, this research demonstrated that increased varus knee joint excursion may be related to a greater magnitude and more abrupt motion of the knee joint articulating surfaces in patients with knee OA.

In the most recent study on varus velocity by Stickley et al.[49], they analyzed twenty-six cadets with no history of overuse injury using them as a control group while six cadets with iliotibial band syndrome (ITBS) served as the injured group. Running data at 4 m/s ± 10% was collected before the start of a 7-month training cycle. The purpose of this study was to prospectively identify gait-related risk factors for the development of ITBS in members of a single ROTC unit focusing on varus velocity and KAM as outputs. Stickley et al.[49] found that the maximum and average knee-varus velocities measured in °/s were significantly different between the injured group (n = 7 limbs) and the control group (n = 26 limbs). The injured group saw a maximum knee-varus velocity of 281.6 ± 117.0 while the control group saw 183.4 ± 73.3. the mean knee-varus velocity in the injured group was 124.9 ± 40.4 and the control group was 63.4 ± 40.8. Additionally, the injured group had a significantly higher maximum KAM compared to the control group. The maximum varus velocity also occurred earlier during the stance phase in the injured group. Concluding, the most important finding of this study was the identification of dynamic varus variables, including varus thrust and KAM as risk factors for ITBS.

Moment/Loading Rate

Little is known of moment rate at this time as the literature exploring such is limited. Searches on PubMed, 19 March 2020 yielded only two results.[21,22] Morgenroth et al.[22] studied twenty-eight participants where 14 were transfemoral amputees and 14 were age and body mass matched controls who underwent knee MRI and assessment and gait analysis determine KAM loading rate, peak, and impulse and an exploratory measure, KAM rate*magnitude. KAM loading

rate was first introduced a decade ago in a study that assessed knee extensor strength.[51] Acknowledging KAM as a proxy for medial knee joint loading, Morgenroth et al.[22] suggests that KAM loading rate may be a more specific means to explore rate of loading at the medial tibiofemoral joint. KAM loading rate was calculated as the maximum instantaneous slope of the KAM curve from initial foot contact to the first peak of the KAM curve. The new variable termed by Morgenroth et al.[22] of KAM rate*magnitude (RM) was calculated as the average of the sum of the products of the rate of rise multiplied by magnitude of the KAM across each set of three adjacent sampling points from initial foot contact to the first peak of the KAM curve. Results showed significant correlation between medial tibiofemoral joint degeneration and peak KAM. The relationship between the MRI score and KAM loading rate and KAM RM were significant after adjusting for peak KAM. However, the relationship between the MRI score and peak KAM was not significant after adjusting for the KAM loading rate and KAM RM in each case. Concluding, this study suggested an independent relationship between KAM loading rate and medial knee degeneration on MRI. These results showed that KAM loading rate is strongly associated with medial tibiofemoral joint degeneration, independent of peak KAM and KAM impulse.

The most recent literature by Doyle et al.[21] studies 12 trans tibial prosthesis users and 12 able-bodied participants who ambulate on level ground, up/down slope and cross slope. Analysis methods included mixed ANOVA statistics with Bonferroni post hoc analyses. KAM rate is defined as the maximum instantaneous slope from foot contact to the first peak of the KAM curve and is measured in N*m/kg/s. This along with KAM impulse can identify individuals with OA. Morgenroth et al.[22] found that KAM rate (KAM-R) was associated with medial tibiofemoral joint degenerative changes using MRI, even after adjusting for KAM peak. A notable finding of this

study was that the down slope limb had a significantly greater KAM-R than all surfaces except bottom slope limb while ambulating cross slope (down slope: 15.35 ± 5.88; up slope: 8.91 ± 2.77; top slope: 12.74 ± 4.09; bottom slope: 14.57 ± 4.99; level slope: 12.95 ± 4.41). KAM-R was the only variable where the intact limb results were significantly greater than the contralateral prosthetic and both able bodied (control) limbs. These results indicate that KAM-R may be more sensitive and therefore a preferred variable to assess knee load-related risk factors across a myriad of surfaces. Concluding, his study confirmed the results of Morgenroth et al.[22] that KAM-R may be the most sensitive measure of KAM-R, peak KAM, KAM impulse and KAM-R*magnitude.

Range of Motion in TKA Patients relating to function

Important in understanding the implications of range of motion and functionality after TKA is the satisfaction of the patients themselves. Van Overschelde et al.[52] studied a surgeon's first 250 total knee replacement operations and 224 completed a patient satisfaction assessment at a two-month follow up. The median ROM at the two-month follow-up was 125° (range, 90°-140°). The overall very satisfied/satisfied rate was 94.6% while eleven subjects (4.9%) reported "OK" satisfaction and only one (0.4%) reported being "not satisfied". Concluding, patients implanted with a second generation medial-pivot system (EVOLUTION®, MicroPort Orthopedics Inc., Arlington, TN, USA) were more satisfied than subjects previously reported for total knee replacements. This 2016 study was one of the only to report total knee replacement satisfaction at a follow-up of less than six months.

Kim & Kim[53] performed a study assessing whether TKA improved functional outcomes and ROM in patients with stiff knees. According to Kim & Kim,[53] the main goals of TKA are pain relief and improvement of function and ROM. This study was conducted with 11 men and 63 women with 86 knees having TKA performed. Post-TKA, a continuous passive motion machine

was used for passive ROM exercise twice daily for 30 minutes each time and physical therapists helped patients to stand or walk along their bedside with a walker or crutches for 30 minutes twice daily. Kim & Kim found that preoperative ROM (40° mean; 10°-50° range) improved substantially after the TKA procedure (102° mean; 65°-145° range). 76% of the operated knees obtained a greater than 90° flexion. Despite disappointing results in knee motion for patients following TKA, the arc of motion on average improved 62°. Despite an average of 102° knee flexion typically being a poor outcome, quality of life and pursuit of activities of daily living were enhanced. Most patients following TKA were able to leave their homes walking whereas before, most could not use the bathroom or leave home without a wheelchair. Knee Society scores and WOMAC scores all improved significantly for overall, physical function, pain, walking stance, social function and emotional function.

Lee et al.[54] performed a retrospective study on 117 patients and 122 knees with a TKA follow up greater than two years. Subjects were divided into two groups based off of severity: severe group (preoperative ROM $\leq 50°$; 18 knees) and the moderate group (preoperative ROM, 50°-90°; 104 knees). This study defined preoperative stiffness as a ROM at the knee $\leq 90°$[55] and 66% of all knees had stiffness caused by OA. Many other studies defined preoperative stiffness as a ROM $< 50°$[53,56] and for this reason, Lee et al.[54] separated patients into the two previously mentioned groups. Statistical significance in this study was determined using ANOVA with Tukey's method and the chi-square test. Preoperatively, the severe group saw a ROM mean of 45° with an increase to a 92° mean postoperatively. The moderate stiffness group saw a ROM mean of 82° preoperatively with an increase to a 110° mean postoperatively. These changes were both statistically significant ($p < 0.001$). Post-TKA, 33% of the severe stiffness group had a recurrence of stiffness while 1% of the moderate stiffness group experienced a recurrence of stiffness.

Additionally, 57% (46) of patients with OA, 67% of patients with rheumatoid arthritis, 13% of patients with infectious arthritis and 20% of patients with traumatic arthritis saw a ROM increase to ≥ 110°. Concluding Lee et al.[54] found that TKA improves ROM following surgery in patients with preoperative stiffness. Clinical outcomes were inferior in knees with more severe preoperative stiffness or stiffness caused by secondary arthritis.

Chen et al.[57] studied 107 patients in a medical center who underwent TKA in Taiwan. The aim of this research was to assess whether aggressive continuous passive motion (CPM) during hospitalization had an effect on pain, ROM and quality of life in TKA patients within six months after operation. The control group received daily basic rehabilitation while the experimental group received daily CPM for > 6 hours together with basic rehabilitation. In total, the experimental group used the CPM for 16.9 ± 6.95 hours. Preoperatively, the experimental group had a ROM of 92.69° ± 14.14° and the control group ROM was 95.13° ± 9.35°. Six months after TKA, the experimental group saw a ROM increase to 125.51° ± 5.99° and 125.13° ± 6.44° for the control group. No significant differences were found between the two groups. Pain intensity was measured on a visual analog scale (VAS). While VAS decreased substantially for both groups from pre-TKA to post-TKA, no significant differences were found between groups at any of the time periods following surgery. Concluding, CPM does not appear to offer benefits in ROM or quality of life; however, it also does not induce more pain in subjects.

APPENDIX A: TKA CONSENT FORM

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
SPONSOR:	Cris Stickley, PhD, ATC
INVESTIGATOR:	Cass Nakasone, MD 888 South King Street Honolulu, Hawaii 96813 United States
SITE(S):	University of Hawaii at Manoa PE/A Complex Room 231, Lower Campus Road Honolulu, Hawaii 96822 United States Straub Clinic & Hospital 888 S. King Street Honolulu, Hawaii 96813 United States
STUDY-RELATED PHONE NUMBER(S):	Cass Nakasone, M.D. 808-522-4232 Cris Stickley PhD, ATC 808-956-3798

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: Data Collection Form

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	

APPENDIX C: WIRB APPROVAL

WIRB
A WIRB-Copernicus Group Company

Certificate of Action

Board Action Date: 07/26/2019	**Work Order Number**: 1-1191527-1
Sponsor: Cris Stickley, PhD, ATC	**Protocol Approval Expires**: 08/24/2020
Sponsor Protocol Number: 2016-007 **Amended Sponsor Protocol Number:**	**Continuing Review Frequency**: Annually
IRB Tracking Number: 20161857	**Panel**: 1
Protocol Title: Biomechanical Analysis of the Oxford® Unicompartmental Knee Implant Design in Osteoarthritis Patients During Level Walking and Stair Negotiation.	

THE FOLLOWING ITEMS ARE APPROVED:
Biomechanical Analysis of the Oxford® Unicompartmental Knee Implant Design in Osteoarthritis Patients During Level Walking and Stair Negotiation.

Please note the following information about this review:

ALL IRB APPROVED INVESTIGATORS MUST COMPLY WITH THE FOLLOWING:

Consistent with AAHRPP's requirements in connection with its accreditation of IRBs, the individual and/or organization submitting shall promptly communicate or provide, and where necessary cause each investigator to promptly communicate or provide, the following information relevant to the protection of human subjects to the IRB in a timely manner:

- Upon request of the IRB, a copy of the written plan between sponsor or CRO and site that addresses whether expenses for medical care incurred by human subject research subjects who experience research related injury will be reimbursed, and if so, who is responsible in order to determine consistency with the language in the consent document.
- Any site monitoring report that directly and materially affects subject safety or their willingness to continue participation. Such reports will be provided to the IRB within 5 days.
- Reports from any data monitoring committee, data and safety monitoring board, or data and safety monitoring committee in accordance with the time frame specified in the research protocol.
- Any findings from a closed research when those findings materially affect the safety and medical care of past subjects. Findings will be reported for 2 years after the closure of the research.

For Investigator's Brochures, an approval action indicates that the IRB has the document on file for the research.

If the board approves a change of Principal Investigator - Once approved, the new Principal Investigator is authorized by the IRB to carry out the study as previously approved for the prior Principal Investigator (unless the Board provides alternate instructions to the new Principal Investigator). This includes continued use of the previously approved study materials. The IRB considers the approval of the new PI a continuation of the original approval, so the identifying information about the study remains the same.

For research subject to continuing review, you will receive Continuing Review Report forms from this IRB when the expiration date is approaching.

Thank you for using this WCG IRB to provide oversight for your research project.

DISTRIBUTION OF COPIES:
Contact, Company
Cris Stickley, PhD, University of Hawaii

This is to certify that the information contained herein is true and correct as reflected in the records of this IRB. WE CERTIFY THAT this IRB IS IN FULL COMPLIANCE WITH GOOD CLINICAL PRACTICES AS DEFINED UNDER THE U.S. FOOD AND DRUG ADMINISTRATION (FDA) REGULATIONS, U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES (HHS) REGULATIONS, AND THE INTERNATIONAL CONFERENCE ON HARMONISATION (ICH) GUIDELINES.

Association for the Accreditation of Human Research Protection Programs, Inc. — Full Accreditation

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