Strategies Utilized to Transfer Weight During Knee Flexion and Extension With Rotation for Individuals With a Total Knee Replacement

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Functional activities in daily life can require squatting and shifting body weight during transverse plane rotations. Stability of the knee can be challenging for people with a total knee replacement (TKR) due to reduced proprioception, nonconforming articular geometry, muscle strength, and soft tissue weakness. The objective of this study was to identify strategies utilized by individuals with TKR in double-stance transferring load during rotation and flexion. Twenty-three subjects were recruited for this study: 11 TKR subjects (age: 65 ± 6 years; BMI 27.4 ± 4.1) and 12 healthy subjects (age: 63 ± 7; BMI 24.6 ± 3.8). Each subject completed a novel crossover button push task where rotation, flexion, and extension of the knee were utilized. Each subject performed two crossover reaching tasks where the subject used the opposite hand to cross over their body and press a button next to either their shoulder (high) or knee (low), then switched hands and rotated to press the opposite button, either low or high. The two tasks related to the order they pressed the buttons while crossing over, either low-to-high (L2H) or high-to-low (H2L). Force platforms measured ground reaction forces under each foot, which were then converted to lead force ratios (LFRs) based on the total force. Knee flexion angles were also measured. No statistical differences were found in the LFRs during the H2L and L2H tasks for the different groups, although differences in the variation of the loading within subjects were noted. A significant difference was found between healthy and unaffected knee angles and a strong trend between healthy and affected subject's knee angles in both H2L and L2H tasks. Large variations in the LFR at mid-task in the TKR subjects suggested possible difficulties in maintaining positional stability during these tasks. The TKR subjects maintained more of an extended knee, which is a consistent quadriceps avoidance strategy seen by other researchers in different tasks. These outcomes suggest that individuals with a TKR utilize strategies, such as keeping an extended knee, to achieve rotary tasks during knee flexion and extension. Repeated compensatory movements could result in forces that may cause difficulty over time in the hip joints or low back. Early identification of these strategies could improve TKR success and the return to activities of daily living that involve flexion and rotation. [DOI: 10.1115/1.4023385]

Keywords: rotary instability, total knee replacement, compensatory strategy, weight transfer

Introduction

Over 600,000 total knee replacement (TKR) surgeries are performed annually [1] and are predicted to rise 673% by the year 2030, with TKR revisions rising by 601% [2]. Due to the increasing physical activity of the aging population, total knee surgery has become common in individuals approaching sixty years old. This population has expectations of maintaining an active lifestyle into their retirement and, therefore, expects positive outcomes after surgery. Expectations will include activities of daily living (ADLs) such as doing laundry, loading the dishwasher, or lifting an item, or higher expectations such as returning to play sports; for example, golf or tennis. In order to meet these expectations, a high axial load needs to be transferred to both legs. Both ADLs and sports require a high axial load with rotary motion at the knee while transferring weight to one leg and maintaining double-stance. Therefore, it is important to explore the manner in which individuals with TKR perform rotary tasks that involve flexion and extension at the knee while transferring weight.

Recommendations for returning to activity post-TKR are varied, considering the risk of imbalanced or excessive implant loading, aseptic loosening, and risk of injury due to a feeling of instability [2]. Most individuals are satisfied with reduced pain and increased function following surgery; however, many assume movement patterns that produce asymmetrical loading to the prosthesis or transfer loading forces to other joints in order to compensate. Improper loading of the knee could lead to an imbalance in the medial and lateral soft tissue structures and wear on the prosthetic device. This imbalance may lead to malalignment or deformity and, eventually, failure of the replacement [3]. The patient may complain of a feeling of "instability" or "weakness" and limit the amount of weight placed on the surgical leg. Instability is one of the most common reasons for TKR revision [4–6] and yet, is poorly defined.

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Clinical and functional stability are defined by different characteristics, but individuals that report a sensation of knee "buckling" or "giving way" are categorized as having knee instability. Clinical stability of the knee is measured by passive tests (both in the sagittal and transverse plane) associated with a subjective complaint, while functional stability may be described as a feeling of instability during an activity. Functional stability is difficult to measure due to the subjective nature of the definition but may be best characterized by measurements of the kinematics and the amount of excursion/translation at the knee joint while performing an activity [7–9]. Some researchers propose that the feeling of instability may be a result of altered kinematics of the knee; however, some individuals with knee instability do not realize compensatory movements at the knee and hip, even when challenged with negotiating obstacles. How is it that some respond well to challenging activities and others do not? Most studies analyze kinematic motion on level walking, ascending and descending stairs, and stepping over objects. The commonality of these activities is that they primarily occur in the sagittal plane. Byrne et al. [10] postulated that knee instability occurs in a medial and lateral direction, resulting in a "giving way" sensation, loss of balance, or fall. Therefore, it is difficult to determine if the feeling of instability is actually related to changes in kinematics or loading of the knee, based on the patient's expectation of a surgical outcome, or pain.

The bulk of the research for capturing loading and kinematics for individuals with TKR involve straight-forward gait, stairs, and sit to stand. Although these activities are important post-TKR, they lack movements in the transverse plane. Pregait strategies, pain, and/or gait velocity may influence knee loading post-TKR [11,12], while sit to stand performance is confounded by quadriceps strength resulting in weight bearing asymmetry [13]. Knee joint loading differs per activity and varies with change in the knee flexion angle. The load can be described over time, such as walking, or as a single point in time depicted in a squat or sit to stand. Although the load may vary with each of these activities, repetition affects the wear on the implant. It is important to identify strategies utilized by individuals with a TKR and relate those to the probable impact they have on the longevity of the implant. Knowledge of the forces on the knee joint during ADLs or recreational activities will also prove valuable for possible implant design and intervention in rehabilitation. Studies have utilized force transducers in the implant to collect specific knee loading [14–16]. Activities such as walking, squatting, stair ascent and descent, and rising from a chair exceed two times body weight (BW) [15]. Treadmill walking generated a lower force than normal level ground walking ($2.0 \times$ BW versus $2.6 \times$ BW, respectively) [17]. Although most studies recruit individuals closely matched to height and weight, it is recommended for any gait analysis to normalize for body weight in order to minimize confounding variables that may exist, including gender [18,19].

Vertical ground reaction force (GRF) is the most common load analysis utilizing force plates or a gait mat for the collection of data. Yoshida et al. [20] found a significant difference in the GRF at 3 months post-TKR. Individuals had less GRF on the operated leg compared to the contralateral leg while performing functional tasks, while Mundermann et al. [15] found a more symmetrical loading with the TKR limb compared to the unaffected leg during sit to stand. The amount of time post-surgery is the difference between these two studies. Mundermann [15] conducted the study 1.5 years after surgery, while Yoshida [20] found differences in the GRF between the surgical leg and the contralateral leg only at 3 months post-TKR but not at 12 months post-TKR. This indicates that if improvements are going to be made post-surgery, it may be reliant on muscle strength development, rehabilitation training, and the activity of the individual pre- and post-surgery. Mandeville et al. [21] supports the fact that individuals may have already developed a strategy presurgery with control of center of mass (COM) within base of support for level walking and over obstacles. Although the TKR individuals had a smaller COM displacement, slower gait, and shorter stride, the differences from the control group were unchanged when compared prior to surgery [21]. Hence, it is difficult to conclude that loading changes are a result of the TKR surgery; rather, the results may have been related to pain. The subjects may have demonstrated a more conservative movement due to pain at less than six months post-TKR.

Although most of the computational models and knee load analyses have been derived from gait cycles, knee loads during functional activities, such as squatting, should be considered since high-flexion is an area of concern for implant design. Squatting with rotation is a functional activity for someone getting in and out of the car or bathtub and transferring a load, such as picking up a child or a laundry basket. Despite the desire to return to recreational sports reported by TKR recipients [2,17,22,23], more consideration should be placed on ADLs that require movements in the transverse plane (flexion/extension with rotation). Our study utilizes a novel approach that facilitates the study of knee loading, rotation, and load transfer during transverse plane motion while in double stance. The objective of this study was to identify strategies utilized by individuals with a TKR while in double-stance transferring load during rotational activities.

Materials and Methods

Twenty-three subjects were recruited for this study: 11 TKR subjects (age: 65 ± 6 years; BMI 27.4 ± 4.1) and 12 healthy subjects (age: 63 ± 7; BMI 24.6 ± 3.8) (see Table 1). All subjects were within 50-75 years of age and excluded subjects with previous hip or ankle surgery, peripheral neuropathy, or a BMI greater than 29. The TKR subjects were further screened for individuals who could flex both knees at least 90 deg and had a unilateral TKR. Subjects were not screened based on the type of knee implant and the extent of participation in rehabilitation.

Each subject signed a consent form approved by the Human Subjects Committee and Institutional Review Board at the University of Kansas Medical Center and approval to be videotaped and photographed. Subjects wore tight-fitting athletic clothing with no reflective material on their clothes or shoes. Anthropometric measurements and bony landmark measurements were collected to configure the computer model and kinematic data using Vicon's Workstation (v 4.5) and the lower body Plug-in Gait Model (Oxford Metrics, Oxford, UK) (see Table 1). Goniometric measurements of the hip and knee's range of motion and manual muscle test of both leg's quadriceps strength (MicroFET2, Hoggan Health Industry, West Jordan, Utah) were collected and recorded for each subject (see Table 1). A KT-1000 measured the anterior translation of the tibio-femoral joint in both knees (see Table 1).

Twenty-four reflective markers (25 mm in diameter) were applied with adhesive to specific bony landmarks and secured with tape. The markers were captured at 120 Hz with an infrared six-camera motion analysis system (Vicon 512, Oxford Metrics,

Table 1 Average (standard deviation) of participant's measurements

	TKA		Healthy
Number of subjects	11		12
Age (years)	67 (6)		65 (8)
BMI	27.7 (4.0)		24.6 (3.8)
Gender	36% F		58% F
Post-op in months	19 (16)		N/A
	Unaffected	Affected	
Quad strength in % BW	0.17 (0.04)	0.19 (0.05)	0.19 (0.03)
KT-1000 (mm)	2.6 (1.0)	2.9 (1.0)	2.4 (0.9)
Knee RoM (deg)	137.9 (6.3)[a]	126.7 (7.6)[a,b]	141.2 (5.7)[b]
Hip RoM (deg)	111.6 (8.3)	107.0 (7.6)	109.1 (10.8)

[a]Affected statistically significant ($p < 0.05$) from unaffected.
[b]Affected statistically significant ($p < 0.05$) from healthy.

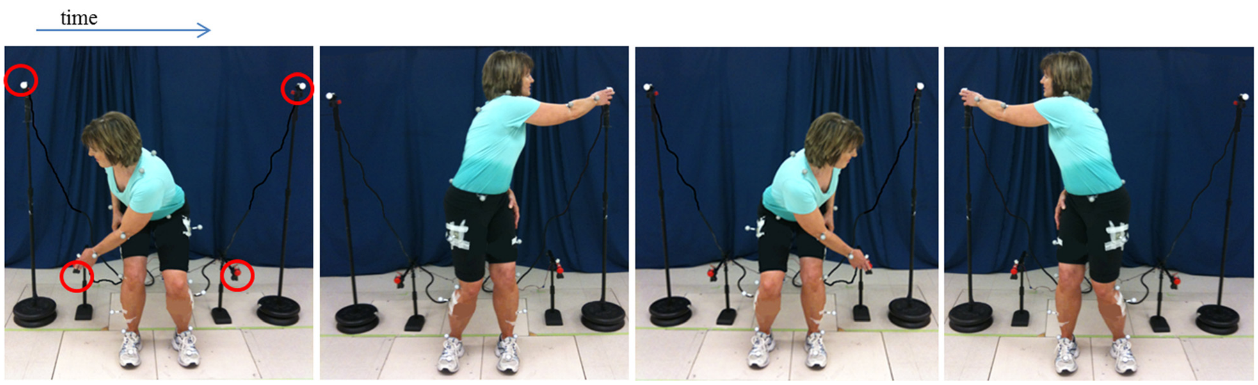

Fig. 1 Equipment set up. Subject performing a low to high (L2H) sequence. The subject performs this sequence three times. Button positions are indicated with circles.

Oxford, UK). The knee axis was determined by a knee alignment device (KAD) that identifies the x, y, and z configuration of the knee joint [24]. In an accuracy study for upper body range of motion by Henmi et al., the Vicon 512 motion tracker had a reliability of ≤ 3 deg [25]. Since the accuracy of the angle measurements are reliant on the placement of the KAD, it can be concluded that the KAD is as reliable as the motion tracker. The Vicon was calibrated according to the manufacturer's specifications. Two force plates (AMTI, Advanced Mechanical Technology, Inc., Watertown, MA) embedded in the floor were used to capture the GRF at 360 Hz. Force plate and analog devices were wired into the Vicon's A/D board and simultaneously triggered by the Workstation software.

A reach test was performed where the subject stood 20 cm in front of a white board and the centerline was referenced by the midline of the subject. The subject reached across his body with his right hand and placed a magnet at his maximum reach, then repeated the motion with the left hand. The distance from the centerline to the magnet was measured and recorded to configure the experimental set up.

For the target touch tasks (TTT) (see Fig. 1), two microphone stands were placed at the recorded reach test least maximum reach value from the centerline of the force plates in the frontal plane. The subject stood with one foot on each of the force plates. Two low buttons were positioned at knee height, just lateral to the knee. The distance from the knee was determined by the comfort level of the subject's ability to bend his knees, rotate to reach, and still press the button. Buttons were clipped to the microphone stands and wired so that when pressed, a confirmatory sound was produced. A static trial with KADs placed on the subject's medial and lateral femoral epicondyles was collected to configure the knee joints.

A description of one of the two tasks collected, either a high-to-low crossover sequence (H2L), or a low-to-high crossover sequence (L2H), was explained to the subject. The subject had the option to perform up to two practice trials. The subjects were instructed to keep their feet planted on the floor and use their legs while reaching to hit the low buttons. The H2L task was defined as when the subject used the opposite hand to cross over his body and hit the button next to his shoulder, switched hands, and crossed to hit the button next to the opposite knee (see Fig. 2). The subject then stood up, pressed the button on the same side by his shoulder with the opposite hand, and did a similar cross over to the other side. This sequence was performed three times at the subject's self-selected pace. Similarly, the L2H activities started with one hand crossing over and pressing the button near the opposite knee, then switched lead hands and pressed the button by the opposite shoulder. This cycle was also performed three times. At any time, if the subject pressed the wrong button, lifted his heels off the force plate, or performed the wrong sequence, a new trial was collected. After each task, the subject was questioned if anything was particularly difficult or challenging.

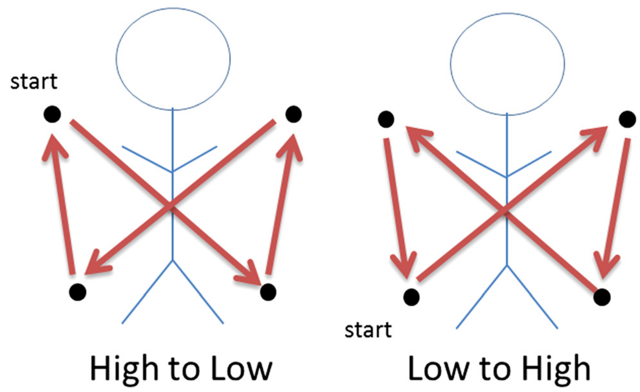

Fig. 2 Sequence of both high to low (H2L) and low to high (L2H) that the subjects performed

The subject's legs were categorized in one of three groups: (1) affected group, TKR leg; (2) unaffected group, the TKR subject's contralateral leg; or (3) the healthy group, the subjects who have had no previous knee injury or surgery. The GRFs were normalized to percent body weight and then according to the task, H2L or L2H. For each of the crossovers, a lead leg was defined as the leg the subject was leaning into on the crossover, or the leg closest to the second button of the sequence. Only five crossover trials were analyzed due to the data collection process; three with the left side leading, two with the right. The lead force ratio (LFR) was calculated by taking the lead leg's GRF divided by the total GRF, thus 0.5 LFR would be when the subject had equal distribution on the lead and lag legs. The trials were interpolated and normalized to a percent button-to-button movement: 0% being when the first button was pressed, 100% being when the second button was released. Any of the five cross over trials that lasted two times longer than the shortest one was eliminated from the data set. The LFR for the affected and unaffected, or healthy were averaged and the standard deviation was calculated for each subject at each percent button-to-button movement. The average and standard deviation of the LFR parameters for H2L and L2H was calculated for all subject groups and a single-factor analysis of variance (ANOVA) was performed ($p < 0.05$). The ANOVAs were performed at 10 and 90% of the button-to-button movement of the averaged data and at the time step of every trial when the subject crossed the 0.5 LFR. These positions (10%, 0.5 LFR, and 90%) were chosen to determine the difference between the three groups when the subject released the first button, the subject had an equal distribution of weight, and when the subject first hit the second button.

Knee angles for each subject were interpolated and cut into the five crossovers. The lead knee's angles were analyzed and time was normalized to percent button-to-button movement. Knee angles for the subjects' affected and unaffected, or healthy knees were averaged for all five trials at each percent of the button-to-button movement. The average and standard deviation of the knee angle parameters for H2L and L2H were calculated for all subject groups and a single factor ANOVA was performed ($p < 0.05$). A single-factor ANOVA was run on the knee angles of the subject at 0.5 LFR ($p < 0.05$). All ANOVAs were further analyzed using Tukey's procedure. To compare the maximum LFR and knee angles for the affected, unaffected, and healthy groups, an independent t-test and paired t-test were performed. Independent t-tests were performed using the affected leg of the TKR compared to the healthy control and then again using the unaffected leg of the TKR compared to the healthy control in order to compare the means between the two groups and separate knee conditions. A paired t-test was conducted when comparing the affected knee to the unaffected knee in the TKR group in order to compare the means of the knees within the same group.

Results

Loading patterns of the affected and unaffected legs during the H2L weight transfer were not statistically different throughout the task, with the unaffected leg transferring a slightly larger load where the maximum LFR for the unaffected leg was 0.71 and maximum LFR for the affected leg was 0.69 (see Table 2). For H2L, the healthy subjects started with less LFR on the lead leg (see Fig. 3), but finished the task with a similar loading to the TKR subjects. A large variation at early to mid-movement was evident with the affected knee (see Table 3). The healthy group also performed the H2L task by transferring their load later than the TKR patients since the healthy's 0.5 LFR occurred later in the button-to-button movement (see Fig. 3(*a*)). In contrast, the L2H LFR for the TKR subject's limbs generally were less than the healthy subject, but had the greatest variation (see Table 3). During mid-movement, the TKR affected leg had the least LFR and transferred their load more slowly than the unaffected and healthy legs (at 62% button-to-button movement compared to 54 and 53%, respectively) (see Fig. 3(*c*)). No statistical differences were found between the three groups at 0.5 LFR for both the H2L and L2H tasks (see Figs. 3(*a*) and 3(*c*)). No statistical difference was found between the groups for the LFR in both the H2L and L2H tasks, although there was a strong trend of statistical difference between the unaffected and healthy subjects during H2L ($p = 0.057$) (see Fig. 3(*a*)) and between the affected and unaffected subjects during L2H at maximum LFR ($p = 0.077$) (see Table 2).

Table 2 Unaffected, affected, and healthy subject's average and standard deviation for maximum lead force ratio and maximum knee angle across all knees. No significant differences were observed.

		Unaffected	Affected	Healthy
H2L	Max lead force ratio	0.71 (0.09)	0.69 (0.09)	0.64 (0.07)
	Max knee angle (deg)	28.03 (9.67)	26.69 (12.96)	38.18 (14.00)
L2H	Max lead force ratio	0.71 (0.09)	0.68 (0.09)	0.71 (0.06)
	Max knee angle (deg)	38.22 (12.98)	34.38 (19.15)	46.13 (16.01)

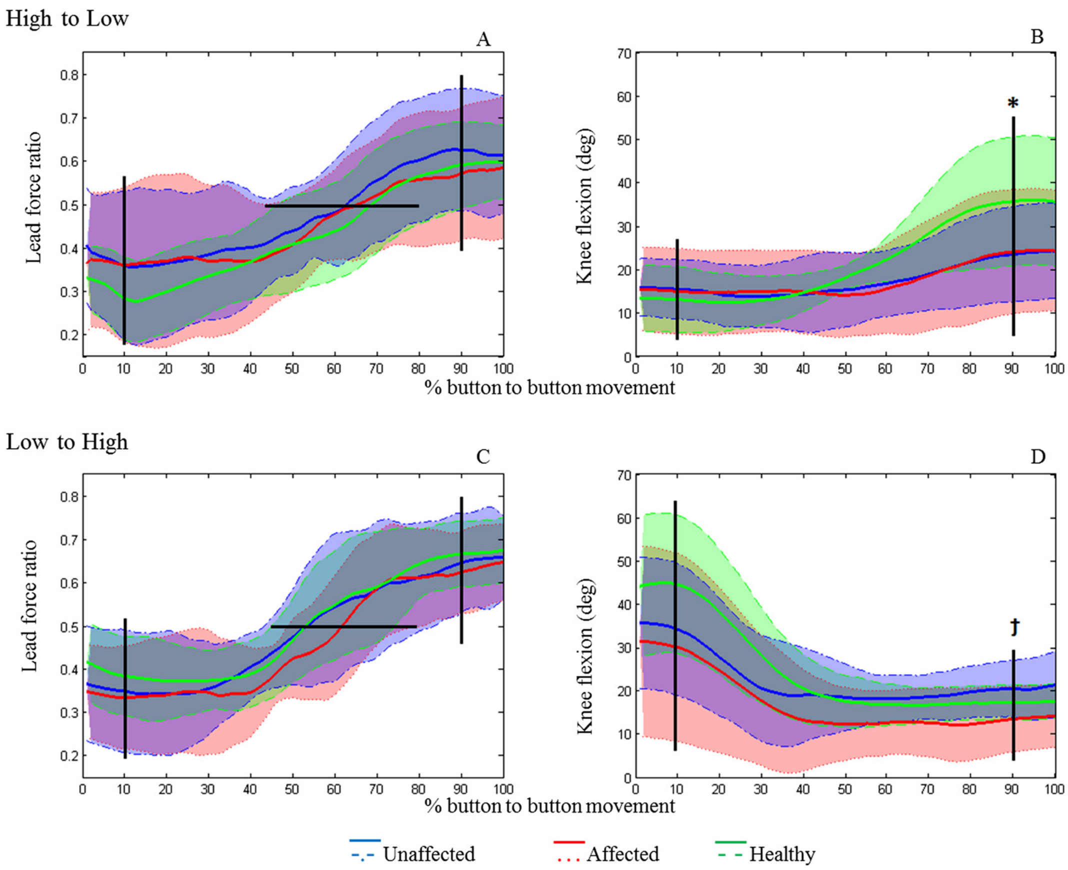

Fig. 3 (*a*) Mean lead force ratio and (*b*) knee flexion angle throughout a H2L activity, and (*c*) mean lead force ratio and (*d*) knee flexion angle throughout a L2H activity. Shaded areas indicate a ±1 standard deviation. Black vertical lines indicate where the subject is at 10%, right after the first button push, and 90%, right before the second button push. The horizontal black line indicates when the subject has 0.5 LFR, or an equal distribution of weight. A single factor ANOVA was performed at each black line. (The * denotes unaffected statistically significant ($p < 0.05$) from healthy. The † denotes unaffected statistically significant ($p < 0.05$) from affected.)

Table 3 Average standard deviations for unaffected, affected, and healthy subject groups while performing high to low (H2L) and low to high (L2H). Values reported for lead force ratio (LFR) and knee flexion angle at 10% and 90% button-to-button movement. The TKR subject values larger than the healthy are indicated in bold.

			Unaffected	Affected	Healthy
H2L	LFR	10% button-to-button	**0.045**	**0.039**	0.033
		90% button-to-button	**0.049**	0.031	0.045
	Angle	10% button-to-button	1.319	1.429	1.928
		90% button-to-button	**3.936**	2.847	3.082
L2H	LFR	10% button-to-button	0.028	0.023	0.050
		90% button-to-button	0.033	**0.040**	0.034
	Angle	10% button-to-button	2.382	2.423	3.234
		90% button-to-button	**1.855**	**2.526**	1.604

Table 4 Unaffected, affected, and healthy's averages (standard deviation) for all percent button-to-button movement that crossed 0.5 lead force ratio and knee angles at the percent the LFR crossed 0.5

		Unaffected	Affected	Healthy
H2L	Percent button-to-button cross 0.5 LFR	56.0 (13)	60.0 (11)	61.0 (18)
	Knee angle (deg) at percent button-to-button = 0.5 LFR	17.8 (8.8)[a]	14.7 (11.5)[a]	25.5 (9.3)
L2H	Percent button-to-button cross 0.5 LFR	60.0 (18)	61.0 (15)	57.0 (15)
	Knee angle (deg) at percent button-to-button = 0.5 LFR	16.5 (8.4)	13.6 (9.0)	17.3 (6.6)

[a]Statistically significant ($p < 0.05$) from healthy.

For both tasks the healthy subjects had a greater knee range of motion throughout the movement sequences (see Figs. 3(*b*) and 3(*d*)) and greater maximum knee flexion (see Table 2). The healthy and unaffected subjects also had a significantly greater goniometric premeasurement knee range of motion than the affected subjects (see Table 1). The TKR subjects tended to keep their legs more extended throughout the tasks, more specifically, during the H2L. While the healthy subjects had a total range of motion of 23.5 deg during the H2L, the unaffected and affected knees only moved a total of 10.5 deg and 10.3 deg, respectively. A significant difference was found between healthy and unaffected knee flexion angles at 90% button-to-button movement, or right before the second button push of the crossover (see Fig. 3(*b*)). Strong statistical trends were also observed at maximum knee flexion for the H2L task between the affected and healthy subjects ($p = 0.055$) and the unaffected and healthy subjects ($p = 0.058$) (see Table 2). A statistical difference in knee flexion was found between the healthy compared to the TKR where the subjects passed 0.5 LFR (Table 4). While the healthy subjects had an average knee angle of 25.5 deg (9.3) when they passed 0.5 LFR, the unaffected and affected knees were only flexed an average of 17.8 deg (8.8) and 14.7 deg (11.5), respectively.

The L2H tasks displayed the greatest amount of knee angle variation between the three groups (see Table 3). At 10% movement, there was a strong trend between the affected and healthy groups ($p = 0.07$), where the healthy subjects were very willing to bend knees to hit the lower buttons; the affected knees were more extended. A statistical difference was seen at 90% between the unaffected and affected limbs of the TKR subjects where the unaffected knee is more flexed throughout the L2H task.

Discussion

The ability to reach for objects within arm's reach while maintaining balance and stability is critical for performing ADLs in a safe manner. Added rotation with knee flexion and extension during this activity provides a challenge to individuals with a TKR [26]. Evidence of a large variation of load transfer for TKR individuals in our study suggests that positional stability of the knee is difficult when challenged during both flexion and extension activities involving rotation. The largest variation during mid-flexion supports previous studies showing instability at 30–60 deg of flexion without the added rotation [27,28]. It is also possible that cognitive planning is ongoing after movement initiation, evidenced by the large variation mid-task [29], a lower LFR, and slower transfer of force in the affected leg of the TKR participants. A delayed time to execute the task by loading the lead leg at a later point of time in the task was demonstrated by the healthy group during the H2L task and the TKR group during the L2H task. This is evident in Fig. 3 as the healthy group unloads the lead leg at the beginning of the H2L task (within the first 10% of movement) while the TKR participants during L2H maintain the same weight through the lead leg (regardless of affected or unaffected) before increasing the load in order to reach the next button. This weight shift for the TKR individuals began at approximately 40% of the total movement to complete this task. Although these differences occur during different cycles of the TTT (extension to flexion in the H2L and flexion to extension for L2H), there must be some reason for this altered timing in loading. A possible explanation is that the change in direction to touch the next button also incorporates a change in purposeful movement trajectory; therefore incorporating acceleration toward a target and the need for deceleration to complete the task. Corrections are needed during the movement in order to complete the task and the delay in loading the lead leg may be a result of cognitive preparation or the need for many corrections of trajectory motion [29]. The affected leg of the TKR group had a lower LFR and delayed loading during the L2H task mid-motion. This suggests the position of mid-flexion may create a need for trajectory correction or cognitive planning of how to achieve the requested task that includes knee flexion into extension while transitioning weight to the affected leg. Surprisingly, the TKR participants did not demonstrate much difference on loading during the H2L task, emphasizing equal distribution of leg loading during flexion tasks or the utilization of a different strategy to shift their center of mass to achieve a task moving into flexion with rotation.

The position of mid-flexion was avoided by the TKR subjects in our study who performed the tasks in more extended positions. The tendency to extend the knee may assist with a feeling of stability during loading and, therefore, the TKR group would be less likely to perform rotary tasks in a flexed knee position. Yoshida [20] found that individuals with a TKR demonstrated unloading of the affected limb up to 3–6 months before equally loading both extremities and continued to use a stiff knee gait pattern post-surgery despite an increase in quadriceps strength. This suggests that knee extension is a more "stable" position and the subjects utilize an alternate strategy to perform the task. Strategies may include loading or unloading the surgical leg. Loading differences could be a possible strategy since a difference was noted between the TKR and healthy group. No differences were found in hip flexion, hip tilt (in the frontal plane), and pelvis rotation between groups despite the fact that the TKR individuals achieved the low button push with a more extended knee than the healthy individuals. This may suggest that the movement to reach the lower button may be achieved by torso flexion (trunk on pelvis) with torso rotation, which would enable a more attainable reach with an extended knee. An analysis of data from the upper torso during the dynamic movements could be analyzed to determine if the TKR participants utilized their torso more than their lower extremities to perform dynamic rotational reaching tasks. These strategies need to be identified in order to alter rehabilitation intervention, avoid implant wear, and prevent future injuries. Compensation in movement contributes to implant wear and altered neuromuscular input (motor control). Early identification and correction of these strategies could improve TKR success and return to activities of daily living tasks that involve rotation.

Participants in this study with a TKR may represent a group that demonstrates alternate knee kinematic and kinetic strategies during rotational tasks. Maintaining a more extended knee and decreased loading of the surgical knee during rotational tasks are two examples of alternate knee strategies that were demonstrated in this study. This is consistent with the literature on obstacle avoidance and level-straight walking studies [7,10,30,31]. Due to the fact that no participant reported difficulty directly after each trial in each task, it is undetermined if any of these strategies are a result of knee instability. Furthermore, considering that conformity of the joint surfaces and anterior translation of the femur on the tibia were not directly measured in our study during the tasks, we can only determine altered knee kinematics, ground reaction, and predicted joint forces as probable strategies demonstrated in the rotary tasks. Although some would argue that the increased loading or altered knee angle may be due to the lack of proprioception and quadriceps control, studies are inconsistent in their findings to support either of these as single factors of activity performance [12,13,32]. Both weight acceptance and knee flexion excursion during gait were not significantly different in TKR participants at an average of 28 months post-surgery [33]. Furthermore, it is argued that the unaffected limb of the TKR participants should not be used as a comparison to the involved limb since both limbs are more symmetrical over time [33,34]. Although it is customary for clinicians and physicians to use the contralateral leg as a standard of "normal" for an individual when testing for range of motion and strength, the comparison of the surgical leg to the opposite leg on the individual should be avoided. Instead, the surgical leg should be compared to the mean of a healthy control group. This is due to the findings in previous studies along with our study that both knees of the individual who underwent surgery will display altered kinetics and kinematics. This may explain the similar performance of the participants in the current study during the load transfer in the H2L TTT and knee flexion during both tasks. Performance may be dependent on time post-surgery, with differences noted in knee flexion excursion at 3 months [35], yet progressing to symmetrical movements within the TKR subjects by 19 months in this current study and 28 months, as documented by Milner [33]. The possible abnormal symmetrical loading of both the involved and uninvolved limb may be the precursor to the progression of osteoarthritis that seems to be prevalent in the contralateral limb of TKR patients, requiring another TKR on the opposite limb [36]. Christiansen et al. [13] chose to examine weight bearing differences one month post-TKR and noted significant asymmetry; unloading the affected leg during a sit to stand activity. Follow-up of these same individuals demonstrated improved symmetry of weight bearing on both limbs at 3 months and was equal to the healthy control group by 6 months. In order to prevent abnormal loading or unloading of either leg following TKR surgery, early intervention addressing equal weight bearing should be a primary goal of post-operative rehabilitation, with the addition of an exercise including a rotary task.

The tendency to unload the affected leg was apparent in the TTT (see Table 2). The TTT may simulate movements such as reaching, getting out of a bathtub, or getting in or out of a car. Therefore, knowing that the TKR individual unloaded the affected extremity more than the unaffected leg provides a reason to incorporate single-leg weight bearing exercises or balance activities in rehabilitation. Rehabilitation intervention that includes biofeedback to promote symmetry in weight bearing during exercises has been suggested by McClelland et al. [37] and proved to produce outcomes similar to the healthy population. Training for symmetry was provided during sit to stand, gait, and balance activities; none of which included rotation as a primary motion. Recognizing this is a single case report, it is difficult to guarantee that practiced intervention will transfer to real life situations, especially due to the inconsistent patterns that are demonstrated in the literature. Individuals with a TKR demonstrated unloading of the affected limb up to 3–6 months before equally loading both extremities and continued to use a stiff knee gait pattern post-surgery despite an increase in quadriceps strength [20]. This is similar to our study, in which the participants demonstrate quick unloading at the beginning of the TTT and lack of knee flexion during squatting. The authors realize that the extent of post-operative rehabilitation with the TKR participants in this study could affect the willingness to put weight on the extremity (loading) and the ability to perform squatting techniques. However, that information was not available at the time of the study; therefore, it should be noted that large standard deviations in each task variable may be a result of individual activity level and/or a response to rehabilitation intervention or lack of intervention. It is also difficult to ascertain if our findings are an actual change due to surgical intervention since data (such as quadriceps strength and knee biomechanics) were not captured prior to surgery. Premeasurements would be beneficial to use as a comparison, however, this study was only conducted on individuals after surgery.

Compensatory movements have been documented as adjustments in kinetic and muscle activity that can affect other joints and influence the performance of functional activities [38]. In the current study, the healthy participants consistently flexed their knees more than the TKR participants throughout both the H2L and L2H tasks. Notably, the healthy group had twice as much knee flexion excursion when compared to both the affected and unaffected knees of the TKR group. At 0.5 of the LFR in H2L the healthy group had significantly greater knee flexion at approximately midline, or equal stance, on each leg. This suggests that the TKR group avoids the mid-flexion range in either knee, possibly due to a feeling of instability, even when standing with equal load on both legs. It is unknown if the TKR group avoided load on the affected leg when leading toward that leg or if they are unable to push off with the affected leg when leading toward the unaffected leg. During the movement from extension into flexion in the H2L task the healthy group flexed their knees 23 deg, while the TKR group flexed approximately 10 deg on either knee. Knee flexion range of motion is commonly referred to as knee excursion during gait analysis. Knee excursion can be compared between the surgical knee and contralateral knee in TKR individuals and may be reduced in the surgical knee for a period of time following surgery. Milner [33] found little difference between the involved knee (11 deg) and uninvolved knee (13 deg) for knee excursion during weight acceptance in individuals 28 months post-surgery, while Mizner and Snyder-Mackler [35] recorded 11 deg in the involved knee and 19 deg in the uninvolved knee at 3 months post-surgery. Although the calculations of knee excursion may be different for each of these studies, it demonstrates that the TKR knee remains in a more extended position up to and over 2 years post-op when performing functional tasks of ambulation and translational movements in the TTT. The added knowledge from the current study of knee biomechanics during a task that involves the transverse plane motion will help health professionals better understand the mechanics and response of the knee following a TKR. By utilizing a rotary task, a dynamic snapshot of both movement and loading of the knee were captured that would not be obtained by direct measurement of anterior-posterior translation in the sagittal plane, as reported by previous studies. The extended knee strategy leads to speculation of how the TKR participants in our study are able to reach the button near the knee in the H2L task where it has been shown that they demonstrate 10 deg knee excursion. Inevitably, torso motion has to be considered, despite the instruction given to each subject to use their legs while performing the crossover task. Collection of each participant's strategy to complete the TTT without cues from the investigator resulted in only one-time instruction at the beginning of the task and no correction of movement during the rest of the cycles. It appears that individuals in the TKR group selected to maintain a more extended knee on either the affected or unaffected knee and find a strategy to accomplish the lower button push. Shakoor et al. [39] recorded higher knee loading on the contralateral side of the individuals with a total hip replacement while walking and greater knee extension and abduction moments when compared to the ipsilateral side. Knowing that loading was transferred to another joint during ambulation 15 months post-surgery, it can be suggested that the TKR participants may have utilized upper torso rotation and altered joint loading to achieve the task of H2L.

Overall, it appears that TKR individuals utilize compensatory patterns, possibly at the torso, for lack of control at the knee. The difficulty of making such statements is that functional outcome measures have been correlated to presurgery status (such as quadriceps strength) [35]; therefore, caution must be taken in the interpretation of the study results due to the fact that we did not collect presurgical measurements. Cadaveric studies testing TKR implants may have difficulty simulating natural knee forces via a robotic or hydraulic device due to failure of the aged tissue. Although joint conformity is controlled, rotary stability in mid-knee flexion requires muscle control and this is difficult to simulate on a cadaveric knee without tissue failure [34–41]. The surgical technique is another factor that is critical for addressing mid-flexion instability of the TKR. Instability is identified as one of the most common reasons for TKR revision [3,42,43]. Therefore, to avoid further need for TKR revisions, a better understanding of weight shift and knee loading during ADLs is needed. Articular loading of the knee is dependent upon the knee angle and can be addressed in post-surgical rehabilitation. In order to decrease the progression toward improper loading of the primary knee replacement that may lead to the need for surgical revision, an early rehabilitation approach to address weight-bearing symmetry needs to be established. Instruction in equal weight bearing of the lower extremities should begin as early as the post-operative protocol permits, along with added balance and proprioception exercises to facilitate weight-shifting during practical tasks. Early intervention to assist in balanced lower extremity weight-shifting should be incorporated with total knee replacement patients to avoid compensatory movements that may create the potential for injury in other joints such as the back, hips, and contralateral knee. Further *in vivo* investigation is necessary to determine if compensatory movement patterns will guide the development for improved implant design, rehabilitation intervention, and a surgical approach for the TKR patient.

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