

BIOMECHANICS OF UNICOMPARTMENTAL KNEE ARTHROPLASTY INDIVIDUALS DURING STEP-UP AND STAIR ASCENT

by

YANG-CHIEH FU (Under the Direction of KATHY J. SIMPSON)

ABSTRACT

Survivor rates of unicompartmental knee arthroplasty (UKA) vary, and reasons for this phenomenon are not clear. Biomechanically, knee joint kinematics affect physical function and long-term survivorship. Therefore, the goal of the first study was to compare, the *in-vivo* tibio-femoral kinematics displayed during a step-up task stair ascent of lateral (LAT) and medial (MED) UKA users. The purpose of the second study was to compare the biomechanics of LAT- and MED-UKA users to control (CON) participants for stair ascent. Fourteen MED-UKA and eight LAT-UKA (N = 22), participants were recruited in the first study. Twenty-six UKA participants (17 MED- and 9 LAT-UKA) participated in the second study, and 26 healthy matched participants were recruited. UKA participants received a CT scan of the operative knee, and the knee kinematics during step-up motion was measured using videofluoroscopy system in the first study. For Study 2, all participants performed stair ascent, and kinematics and kinetics were calculated. One-way ANOVA tests were used to examine differences between MED- and LAT-UKA groups in the first study. Paired t-tests were used to examine differences between medial and lateral condyles in each UKA group in the first study, and were used to examine differences between MED/LAT-UKA and MED/LAT-CON groups in the second study.

In general, the predictions that LAT-UKA would display different tibio-femoral kinematics

than MED-UKA during step rising and that both UKA groups would display differences for kinematics and kinetics compared to their control groups for stair ascent were not supported. This was likely due partly to small sample size and inter-individual difference for some variables. However, both MED- and LAT-UKA individuals displayed knee kinematics that were mostly typical when compared to values of healthy knees from the literature (Study 1) and their respective control groups' values (Study 2).

Based on findings of both studies, both MED- and LAT-UKA appear to indicate that both UKA groups demonstrated typical knee biomechanics. Furthermore, current results might suggest that MED-UKA individuals show some slightly better biomechanical outcomes than LAT-UKA individuals.

INDEX WORDS: UKA, stair negotiation, videofluoroscopy, joint kinematics, joint kinetics

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YANG-CHIEH FU

B.S. National Central University, Taiwan, 1999

M.S. National Taiwan University, Taiwan, 2003

A Dissertation Submitted to the Graduate Faculty of The University of Georgia in Partial
Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2011

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YANG-CHIEH FU

Major Professor: Kathy J. Simpson

Committee: Cathleen Brown
Ormonde M. Mahoney
Kevin McCully
Steven Olejnik

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
May 2011

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere appreciation to my advisor, Dr. Kathy J. Simpson, who had paid the most patience on me and guide me to the right way for research. I would also like to thank my committee members, Dr. Ormonde M. Mahoney, Dr. Steven Olejnik, Dr. Kevin McCully, and Dr. Cathleen Brown for their support and advice on the dissertation project. I would like to thank Bradley Bowser who helps in building stairs for the project. I would like to thank the lovely Biomechanics Laboratory members, Jae Pom Yom, Dalbeer Pawar, and Jayma Lallathin for their help in data collection. I would like to thank Dr. Takahiko Kiyama for help on fluoroscopy data collection. I would also thank the staffs in the department of radiology at St. Mary's Hospital to help me collect CT images. Especially, I would like to thank the Fitness Center in the Department of Kinesiology and the Osher Lifelong Learning Institute at UGA, to allow me to recruit participants for this study.

I would especially like to deliver honest appreciation to Dr. Ormonde M. Mahoney, who put extra time and offer to give me fully support to accomplish my dissertation. I would like to thank financial assistance of Athens Orthopedic Clinic Foundation to allow me to accomplish this study. I would like to thank Athens Orthopedic Clinic Staff, Megan Johnson for her help on contacting patients, and Tracy Kinsey for her suggestions and negotiations for this project. I would like to thank other Athens Orthopedic Clinic staff, Debbie Ashburn, Fermer C. "Butch" Dent, and all others whom are not listed here. I really appreciate all your help.

At last, I cannot even begin to give enough gratitude for my family, my parents and younger sister who endured the most during my Ph.D. time in my life. Without their love I could never finish my degree. I love you, my family.

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CHAPTER 1

INTRODUCTION

Background

Globally, as the number of older adults increases, the number of people who will develop osteoarthritis (OA) will also increase (Hootman & Helmick, 2006). It is estimated that approximately 10% of the world population who are 60+ years old have symptomatic problems caused by OA (Symmons, Mathers, & Pflieger, 2000). OA is a degenerative joint disease that has serious repercussions for the individuals who suffer from it and for society. First, severe OA can become extremely painful, causing the individual to lose mobility (Buckwalter, Saltzman, & Brown, 2004). Second, the incidence rate is growing. In 2005, it was reported that the U.S.A. has an estimated 26.9 million adults with OA, an increase of 1.8 million people from 1990 (Lawrence et al., 2008). Moreover, the number of people who have OA in the U.S.A. will be nearly 67 million by 2030 (Hootman & Helmick, 2006).

When a person has advanced knee OA and nonsurgical treatments do not improve symptoms, knee arthroplasty generally is suggested (Sarzi-Puttini et al., 2005). During a total knee arthroplasty (TKA), the entire tibio-femoral joint is replaced (Figure 1.1a), the anterior cruciate ligament is removed, and the posterior cruciate ligament may also be removed, depending on the implant design. In 2003, 235,200 people received primary or revision TKAs in the US (Kurtz, Ong, Lau, Mowat, & Halpern, 2007). As the number of people with OA continues to rise, it is estimated that in the US, people who need a primary or revision TKA will also increase to 3.75 million by 2030 (Kurtz et al., 2007).

These current and future knee arthroplasty patients want to continue active lives without pain, and use their implanted knees for as long as possible before undergoing another replacement surgery. Therefore, to satisfy these needs of this growing knee arthroplasty population, efforts to improve knee implant components and surgical procedures used in knee arthroplasties are necessary.

One result of these efforts is the recent re-emergence of unicompartmental (or unicondylar) knee arthroplasty (UKA). Redesigned components and modified surgical procedures are now used compared to the first design of UKA that was introduced and applied on OA patients in the 1970's (Marmor, 1973). As Figures 1.1 and 1.2 demonstrate, during an UKA, only the diseased lateral or medial femoral condyle and corresponding tibial plateau of the knee joint are replaced. Hence, an orthopaedic surgeon might choose a UKA instead of a TKA if only one compartment needs to be replaced (Tria Jr, 2002).

Several benefits of a UKA compared to a TKA, have been suggested that UKA has 1) smaller incision, more intact soft tissues, less postoperative pain and less hospital time (Verdonk, Cottenie, Almqvist, & Vorlat, 2005), 2) similar or slightly better clinical outcomes (Fuchs, Tibesku, Frisse, Laa, & Rosenbaum, 2003; Heyse & Tibesku, 2010; Price et al., 2004), and similar or slightly better knee flexion/extension range of motion (Griffin et al., 2007; Laurencin, Zelicof, Scott, & Ewald, 1991). From biomechanical point of view, the most important purported benefit is that a UKA keeps more knee tissues intact, such as both cruciate ligaments, and the nonreplaced tibio-femoral compartment (Verdonk et al., 2005). During the original concepts of UKA, McKeever (1955) surmised that, by keeping much of the original knee tissues intact, knee motion after UKA surgery should be closer to that of a typical knee joint. For this reason, it was also postulated that a UKA also should display better kinematic outcomes than a TKA.

However, evidence to that effect is inconsistent and not strong. Recently, Griffin (2007) reviewed current UKA studies and reported that, compared to TKA patients, UKA patients reported similar levels of pain during post-operative recovery, slightly better functional scores such as Knee Society Scores (KSS), and greater range of motion (ROM) of the knee. Moreover, survival rates, that is, the percentage of people who still have their original UKA after a specified number of years post-operation, were not as high as desired. On average, survival rates were lower than 70% within 10 years in the 1970s; survival rate at 10 years in the 1980's, however, improved to about 80% (Tanavalee & Yuktanandana, 2003).

At present, it is unclear why there is such variance in the reported survival rates of UKA. Among recent studies, 10-year survival rates of UKA have varied from 80% (Koskinen, Paavolainen, Eskelinen, Pulkkinen, & Remes, 2007) to 98% (Geller, Yoon, & Macaulay, 2008). In comparison, there is consistently high survivorship of TKAs (over 90% for 15 years) reported (Ermnerson, Moran, & Finder, 1996; Falatyn, Lachiewicz, & Wilson, 1995; Ranawat, Flynn, Saddler, Hansraj, & Maynard, 1993). Therefore, the potential for shorter wear time may lead some surgeons to perform TKA instead of UKA, even though there still are insufficient data to support or refute this notion (Gunther et al., 1996; Verdonk et al., 2005).

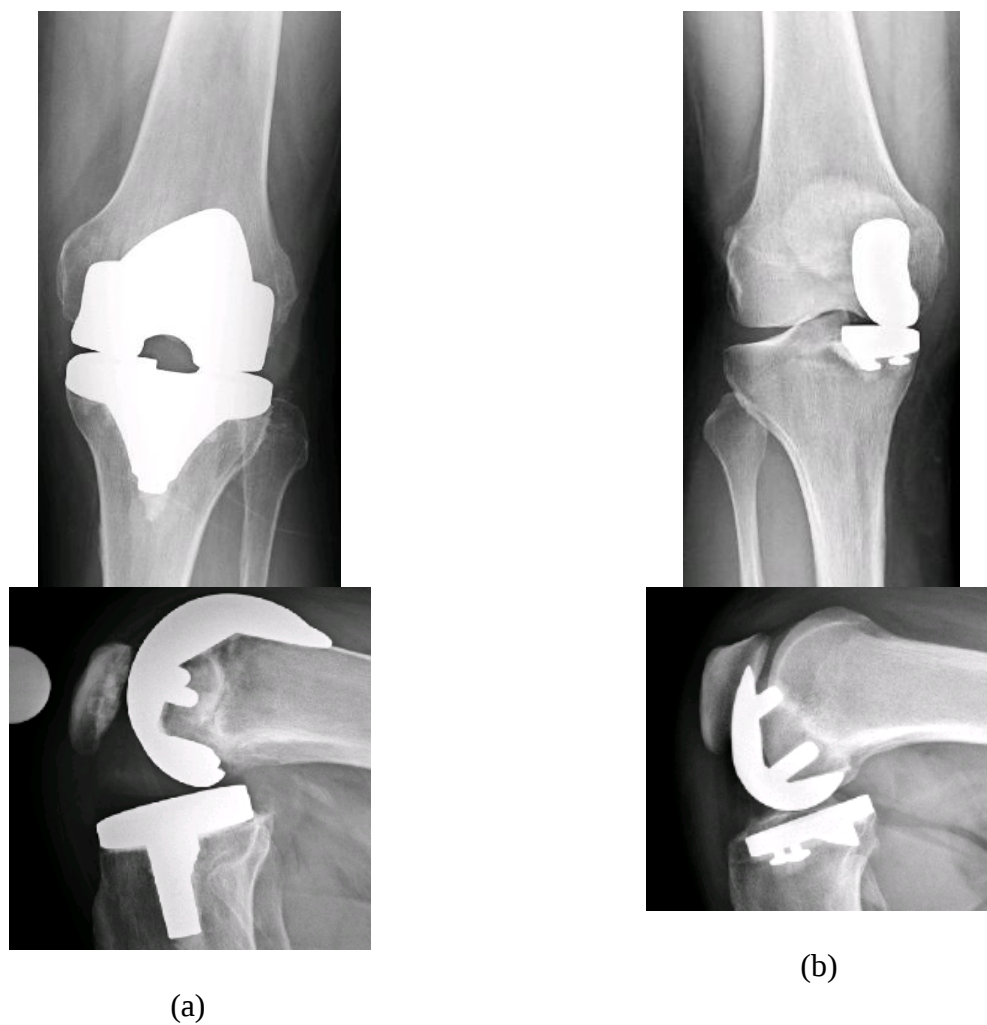


Figure 1.1 Radiographs of a) total knee arthroplasty and b) unicompartmental knee arthroplasty (UKA) during standing and at maximum flexion. A UKA only replaces one compartment (medial or lateral) of the tibio-femoral joint.

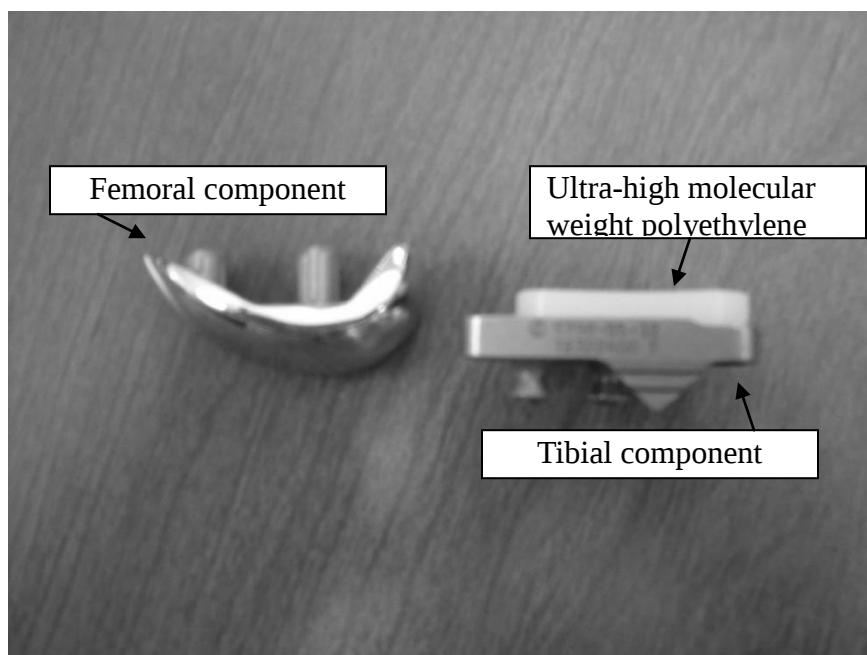


Figure 1.2 Zimmer unicompartmental knee replacement. The metal parts replace the damaged bones and a plastic insert is put between metal parts to serve as cartilage.

It is unclear if the success of a UKA is related to the compartment replaced. Reported survivorship rates show mixed results (Tanavalee & Yuktanandana, 2003). It was reported that LAT-UKA have a 67% survival rate at 10 years (Gunther et al., 1996), but another study shows an 89% survival rate at 5 years (Ohdera, Tokunaga, & Kobayashi, 2001). On the other hand, MED-UKA have a 90% survival rate at 10 years (Naudie, Guerin, Parker, Bourne, & Rorabeck, 2004). Thus, it is not clear whether LAT-UKA have similar or lower survival rates compared to MED-UKA, nor what mechanisms may explain the lower 10-year LAT-UKA survival rates. Furthermore, knowledge regarding the lower extremity biomechanics of today's UKA patients, especially of LAT-UKA is limited. Hence, we need a better understanding of biomechanics of both MED- and LAT-UKA to help doctors, potential UKA candidates and implant designers.

Therefore, the research questions of this current study are; 1) *what are the knee kinematics*

of MED- and LAT-UKA participants (PP) during a weight-bearing knee extension task, and 2) how do MED and LAT knee joint kinematics and kinetics displayed compare to those of typical knee joints during stair ascent? To answer these questions, two studies were undertaken.

Purposes of the studies

The purposes of the studies were as follows:

Study #1: To describe the *in-vivo* kinematics of the knee joint of MED- and LAT-UKA individuals for a step-up task via videofluoroscopy.

Study #2: To determine if MED-UKA and/or LAT-UKA individuals display altered kinematics and kinetics during stair ascent as compared to matched, control individuals (CON).

Premises of the study

For several reasons, it is predicted that: a) MED-UKA individuals would have different biomechanical behaviors compared to LAT-UKA individuals, and b) MED- and LAT-UKA would have different knee biomechanical behaviors compared to healthy individuals. Soft tissue release during surgery, different biomechanics between medial and lateral condyles of a healthy knee, and joint laxity after UKA will likely influence the biomechanics of the knee joint after receiving UKA (Sharma et al., 2001). Associations between these factors and UKA are illustrated in Figure 1.3.

First, although it is mostly accepted that outcome of UKA is influenced by postoperative alignment (Heck, Marmor, Gibson, & Rougraff, 1993; Kasodekar, Yeo, & Othman, 2006; Ridgeway, McAuley, Ammeen, & Engh, 2002; Squire, Callaghan, Goetz, Sullivan, & Johnston,

1999; Tanavalee & Yuktanandana, 2003), postoperative alignment is closely related to preoperative deformity. The operated compartment of a UKA candidate is first predetermined by his/her preoperative valgus/varus alignment. Preoperative valgus/varus alignment of the UKA thus will affect soft tissues release including ligaments and muscles surrounding the knee joint. During a UKA operation, higher preoperative deformity requires more soft tissue and ligament releases to retension the tissues and realign the tibio-femoral joint on the frontal plane compared to lower preoperative alignment (personal communication with Dr. Mahoney). Consequently, tissue releases of UKA might significantly influence knee biomechanics after UKA. However, these releases are difficult to accomplish during an UKA, and postoperative alignment is hard to maintain.

Second, the lateral and medial condyles of the femur have different biomechanical behavior mainly due to the morphology of the knee joint structures and the locations of the axes of rotation of the tibio-femoral joint. The kinematics of the knee joint is mainly guided by the geometry of what and surrounding soft tissues of the knee, including the ligaments and meniscus (cartilage) (O'Connor, Lu, Wilson, Feikes, & Leardini, 1998). Therefore, within the healthy knee joint, the lateral condyle has more anterior-posterior translation than the medial condyle (Hill et al., 2000; Iwaki, Pinskerova, & Freeman, 2000). It is likely that the kinematics of the tibio-femoral joint will change if the geometry of the bones and material/mechanical properties of surrounding soft tissues change. Consequently, it is assumed that MED-UKA, LAT-UKA, and healthy knees all behave differently.

Furthermore, a MED-UKA versus a LAT-UKA has different surgical considerations for ligament releases during surgery. For example, a surgeon can choose the level of tissue release of the deep medial collateral ligament (MCL), posterior bundle of the superficial MCL, and anterior

bundle of the superficial MCL in MED-UKA, and release of the lateral collateral ligament (LCL) and ilio-tibial tract. Hence, release of different tissues for a MED-UKA and a LAT UKA may result in different knee biomechanics.

Therefore, the last reason, joint laxity after UKA, is another potential biomechanical factor that influences postoperative performances of the knee (Sharma et al., 1999; Teichtahl, Wluka, & Cicuttini, 2003). This is biomechanically meaningful because if the knee joint has greater laxity due to release of surrounding soft tissues including ligaments and muscles after UKA, the knee joint will have different knee joint kinematics and potentially cause abnormal loading at either the implant or healthy compartment of the UKA knee. Thus, if there is the abnormal loading of the knee due to joint laxity, then potentially contributes to unsatisfactory clinical/functional performances of the UKA knee, and may progress of OA at the healthy compartment of the UKA knee (Sharma et al., 1999).

Thus, it is surmised that for both MED- and LAT UKA, differences should be demonstrated in the frontal and transverse planes, and not in the sagittal plane based on factors described before and previous studies. It has been reported that UKA does not demonstrate different kinematics on sagittal plane compared to healthy individuals (Fuchs, Tibesku, Frisse, Laa, & Rosenbaum, 2003; Webster, Wittwer, & Feller, 2003). However, joint laxity does exist at the knee joint (Banks, Fregly, Boniforti, Reinschmidt, & Romagnoli, 2005). MED-UKA individuals should have more adduction and LAT-UKA individuals have more abduction compared to healthy individuals due to soft tissue releases at the lateral or medial side of the knee. Consequently, corresponding joint moment will also be different due to factors described.

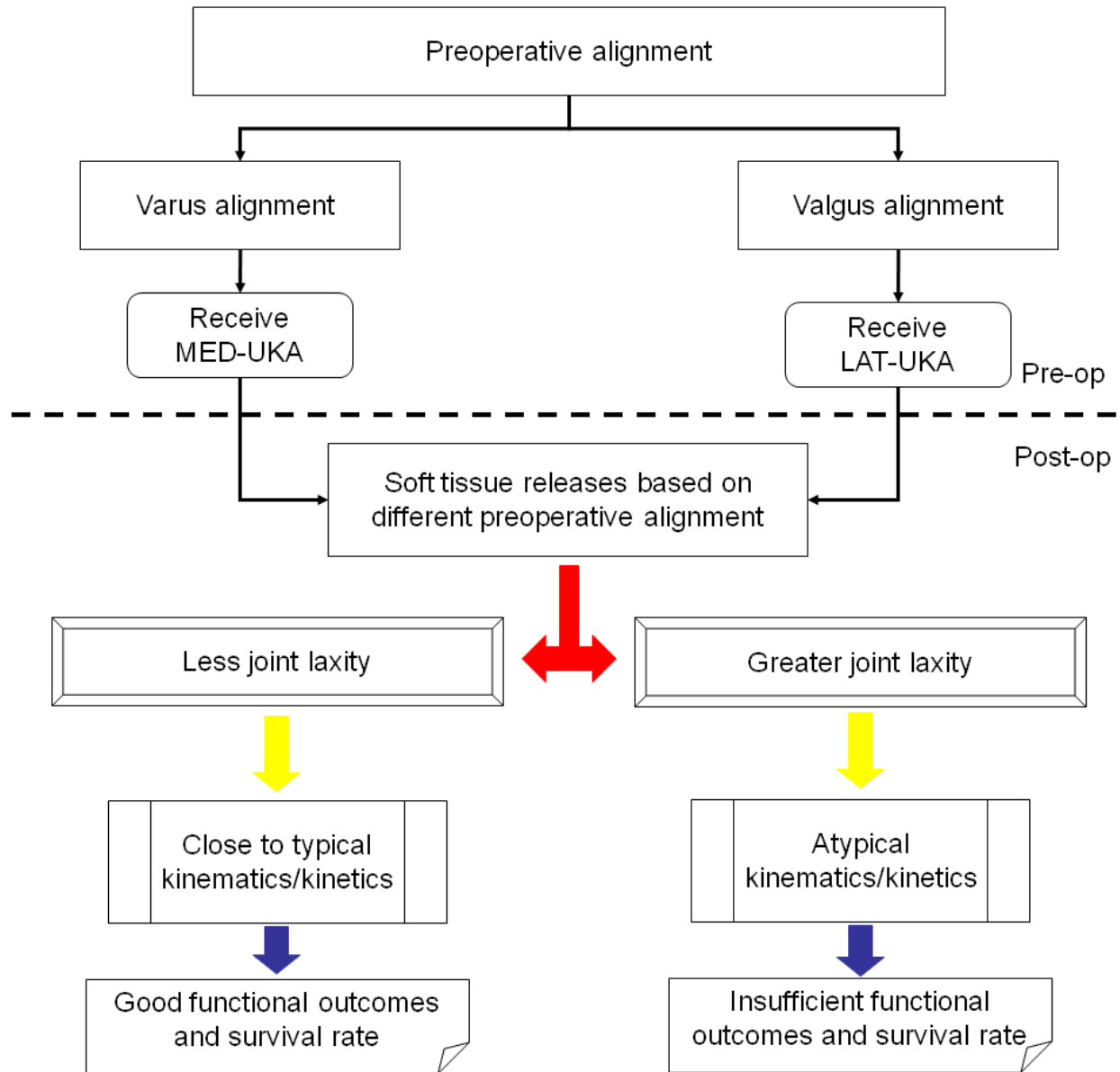


Figure 1.3 Premises for current study. After receiving unicompartmental knee arthroplasty (UKA), soft tissue releases and joint laxity will then affect biomechanical behavior and potentially reduces the long-term survival rate and functional outcomes.

Hypotheses

For Study#1, “*Videofluoroscopic comparison of the knee joint kinematics exhibited during a step-up maneuver of MED- and LAT-UKA individuals*”, the hypotheses are as follows:

For *in-vivo* knee kinematics of the MED-UKA participant (PP) during a step-up motion, compared to those of the LAT-UKA PP will exhibit:

1. Greater AP translation of the medial condyle and less AP translation of the lateral condyle.
2. Less internal rotation displacement and abduction displacement.

For study#2, “*Biomechanics of medial and lateral unicompartmental knee arthroplasty individuals during stair ascent*”, the hypotheses are as follows:

For *in-vivo* knee kinematics and kinetics of the UKA limb during the stance phase of stair ascent on the 1st step, compared to the corresponding limb of their matched CON group:

1. MED-UKA will exhibit greater adduction and less internal rotation displacements.
2. LAT-UKA will exhibit greater abduction and internal rotation displacements.
3. MED-UKA will exhibit greater peak knee adduction and internal rotation moments.
4. LAT-UKA will exhibit less peak knee adduction and internal rotation moments.

Significance of the study

With improvements on implant design and surgical techniques of UKA, more surgeons consider UKA is a good treatment for OA (Tanavalee & Yuktanandana, 2003). However, survival rates of modern UKA vary and knowledge regarding LAT-UKA outcomes is especially limited

(Geller et al., 2008; Gunther et al., 1996; Koskinen et al., 2007; Verdonk et al., 2005).

Furthermore, differences between MED- and LAT-UKA are not clear, and biomechanical studies of UKAs are lacking. Although MED-UKA has been studied by Banks (2005), limited LAT-UKA study has been undertaken (J.-N. A. Argenson et al., 2002), and kinematics of the healthy compartment has not been reported after UKA. Thus, study #1 aims to elucidate the kinematics of MED- and LAT-UKA, including the replaced and healthy compartment of the knee.

UKA kinematics and kinetics has been reported during level walking (Fuchs et al., 2005; Webster et al., 2003). However, joint kinetics and kinematics in frontal and transverse planes have not been described yet. Stair ascent has been considered a demanding activity (Andriacchi & Hurwitz, 1997), and UKA stair ascent was studied in 1986 (Weinstein, Andriacchi, & Galante, 1986). However, biomechanics of UKA is out of date, and the modern UKA has not been investigated. Additionally, how UKA individuals compare to healthy individuals has not been fully discussed. Thus, study #2 aims to elucidate the three dimensional biomechanics including joint kinematics and kinetics of MED-UKA and LAT-UKA compared to corresponding matched healthy individuals. The findings of both studies will provide both kinematics and kinetics data of the lower extremity in order to explain how the MED- and LAT-UKA affect the knee biomechanics.

It would be important for implant designers to improve design of UKA, and for doctors to make decision for a UKA candidate from our finding. Additionally, progression of OA on the healthy compartment after UKA has been reported (J. N. A. Argenson, Parratte, Bertani, Flecher, & Aubaniac, 2008; Heyse & Tibesku, 2010). Results of both studies might provide data to investigate evidence for OA progression on the healthy compartment after UKA, and factors might contribute to OA progression, eventually help to improve survival rate of UKA.

CHAPTER 2

REVIEW OF LITERATURE

The knee joint is a complex joint of the human locomotor system, which has made designing successful artificial joints very challenging. Hence, the literature review begins with the basic anatomy of the knee joint, followed by epidemiology of OA, introduction of unicompartmental knee arthroplasty (UKA) and total knee arthroplasty (TKA) and the biomechanics displayed during stairs activities between individuals with healthy knee joints and people who have had an UKA or TKA). Factors that are known or suspected to lead to a successful UKA will also be discussed.

Anatomy of the knee

The knee joint is a unique and complex joint in the human body, because there are competing goals to be balanced with mobility. It is needed to move the body in innumerable directions effectively during weight-bearing activities, yet the joint must have sufficient stability to maintain balance and prevent tissue damage to structures of the knee joint. Knowledge of the knee joint anatomical functions helps understanding of associated biomechanical research. The knee joint is consisted by four major bones, namely femur, patella, tibia and fibula (Moore & Dalley, 1999). The three articulations in this region are named for the two bones that comprise the given joint: the tibio-femoral joint (will also be called the “knee joint” in this document) and patello-femoral joints, and the tibio-fibular joint. There are five important ligaments and one tendon, namely anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), lateral collateral ligament (LCL), medial collateral ligament (MCL) and patellar ligament. LCL and

MCL are also called fibula collateral ligaments. Covering the articulating surfaces of the bones of a healthy joint is articular cartilage. Attached to the surface of each of the medial and lateral compartments of the proximal tibia, there is a semi-lunar shaped fibrocartilage tissue called a meniscus.

Movement of the knee joint has three translations and three rotations, totally six degree of freedom. Healthy human knee joint flexion-extension range of motion (ROM) is approximately from 0 to 140 degrees (Nordin & Frankel, 2001). During gait, the healthy knee joint flexion-extension ROM is approximately from 0 to 70 degrees (Murray, Drought, & Kory, 1964). However, the knee joint movement is not pure single plane motion. The tibia has internal rotation during knee joint flexion and externally rotation during extension. This is called screw-home mechanism (Weber & Weber, 1836). This is because in a healthy knee joint, the medial femoral condyle is about 1.7 cm longer than latercal femoral condule, which is suggested that the geometry of the bone will influence the movement of the knee.

These ligaments, tendon, and cartilage take charge of linking bones surrounding the knee joint and guide knee joint motions (Wilson, Feikes, & O'Connor, 1998; Wilson, Feikes, Zavatsky, & O'Connor, 2000). The mechanical purposes that these soft tissues serve relative to knee joint mechanics are listed in Table 2.1 (Fu, Harner, Johnson, Miller, & Woo, 1993; Nordin & Frankel, 2001). Forces that act to move the body effectively also act to increase/decrease knee joint stability as well as affect the integrity of the knee joint's tissues. For example, knee extensor muscles contribute to the tibio-femoral compressive stresses during weight-bearing activities, that in turn, may stimulate tibial bone mass improvement (bone remodeling) and/or wear down the articular cartilage (Nordin & Frankel, 2001). Therefore, to achieve optimal functioning of a knee joint partially or fully replaced, requires an understanding of healthy, typical knee joint

anatomical structures and knowledge of how they behaves biomechanically.

Table 2.1 Mechanical purposes of the knee joint surrounding ligaments and meniscus. Movements are defined as the tibia relative to the femur.

Soft tissue	Mechanical purpose
Anterior cruciate ligament	• Primary restraint for anterior translation • Regulate screw-home mechanism
Posterior cruciate ligament	• Primary restraint for posterior translation • Regulate screw-home mechanism
Medial collateral ligament	• Primary restraint for adduction (valgus) • Primary restraint for external rotation
Lateral collateral ligament	• Primary restraint for abduction (varus) • Primary restraint for internal rotation
Patellar ligament	• Transfer forces generated by quadriceps to tibia
Meniscus	• Guide knee joint motion by its geometry • Distribute loading evenly onto tibia

Knee joint arthroplasty for osteoarthritis

Osteoarthritis (OA) is a degenerate disease in the human joints (Buckwalter, Saltzman, & Brown, 2004), and weight bearing joint has greater clinical impact than non-weight bearing joints. Generally, 13.9% of adults aged from 25 and older have OA and 33.6% (12.4 million) of those over 65 (Lawrence et al., 2008). OA population continuously grows. In 2005, it was reported that the US has an estimated 26.9 million adults up from 21 million in 1990 have OA (Lawrence et al., 2008). It was reported that incidence rate of the knee OA is 240 per 100,000

people, compared to the hip OA has only 88 per 100,000 (Oliveria, Felson, Reed, Cirillo, & Walker, 1995). Cost of OA is approximately \$7.9 billion of knee and hip replacements in 1997 (Lethbridge-Çejku, Helmick, & Popovic, 2003), and total annual disease costs is approximately \$5700 in 2000 (Maetzel, Li, Pencharz, Tomlinson, & Bombardier, 2004). It is approximately 20–35% of the knee OA and about 50% of the hip and hand OA may be genetically determined (Felson, 2004; Felson & Zhang, 1998). Estimated modifiable risk factors are excess body mass, joint injury, occupation due to excessive mechanical stress, structural malalignment, and muscle weakness (Felson, 2004; Felson & Zhang, 1998; Rossignol et al., 2005). Nonmodifiable risk factors of OA are gender, age, and race (some Asian populations have lower risk) including genetic effects. It is obvious that most of the modifiable risk factors are biomechanical associated. When a person has an advanced OA, it is generally suggested receiving knee arthroplasty, which replace the knee joint by metal components, to remove pain and recover functions of the knee mobility and stability.

Total knee arthroplasty (TKA) has been the main choice of treatment for advanced OA over the last few decades. The knee joint functions are reconstructed by replace the contact surfaces between femur, tibia and patella. Previous studies showed that less than 10% of TKA patients needed revision surgery after 10 to 15 years for most commercial TKR's (Ermnerson, Moran, & Finder, 1996; Falatyn, Lachiewicz, & Wilson, 1995; Ranawat, Flynn, Saddler, Hansraj, & Maynard, 1993). Despite the excellent long-term survivorship, there are however improvements that can be made, such as wear resistance and functional range of motion, as well as potential problems that may emerge in the future. It is noted that good survivorship does not necessarily imply satisfactory functional recovery. Therefore, it is essential to assess the functional performance via biomechanical analysis for better understanding of knee replacement advantages

and disadvantages.

Unicompartmental (or unicondylar) knee arthroplasty (UKA) is another new choice of knee OA. Unlike TKA replaces whole tibiafemoral and patellofemoral joint surfaces, it resurfaces only the symptomatic component of the knee, either the medial (MED-UKA) or lateral (LAT-UKA). The design concept for UKA is, with keeping more intact knee anatomy especially ACL and PCL after surgery, knee performance after surgery theoretically should be closer to normal knee than TKA. This concept was first conceptualized by McKeever in the early 1950s (McKeever, 1955) and later led to the use of the first unicompartmental replacement (Marmor, 1973). UKA however had lower survivorship rate in the 1970s, and seems be affected by implant design, surgical techniques, alignment of the knee, and progression of OA (Heck, Marmor, Gibson, & Rougraff, 1993). Thus, the most preferred surgical treatment for server OA is TKA rather than UKA. UKA has been recently due to improved implant designs and minimal incision surgical techniques (Tanavalee & Yuktanandana, 2003). Compared to TKA, it is purported that modern UKA has small incision, keeps more soft tissues intact, less postoperative pain (Fuchs, Tibesku, Frisse, Laa, & Rosenbaum, 2003), reduces hospital time, slow progression of OA in nonsurgical condyle, better range of motion, and easier to revise to a TKA compared to high tibial osteotomy (Tanavalee & Yuktanandana, 2003). However, there is limited evidence to support those assumptions. Furthermore, knowledge regarding to today's UKA especially LAT-UKA is limited. Thus, some surgeons believe UKA surgery is not as good as TKAs, although there are insufficient data to support or refute this notion (Gunther et al., 1996; Verdonk, Cottenie, Almqvist, & Vorlat, 2005). Moreover, for LAT-UKA, this issue is particularly controversial. Current facts for UKA are summarized below.

Survivorship of UKA

Survivorships before 1970s were averagely lower than 70%, about 80% in 1980s (Tanavalee & Yuktanandana, 2003), and lack of long-term survivorship. This was possibly due to design of replacement was not sufficient and required different surgical techniques from TKA. Compared to the high survivorship of TKA (Ernerson et al., 1996; Falatyn et al., 1995; Ranawat et al., 1993), contemporary surgeons preferred using TKA instead of UKA. Recent UKA survival rate in the literature are summarized in Table 2.2.

Table 2.2 Results of modern UKA survivorship in the literature. Bolded numbers in survival rate at 10 years means survival rate under 90%.

Study		UKA type			follow-up	Survival rate at 10 yrs (%)
		Med	Lat	bi		
Scott	1991	88	12		8-12 yrs	85
Gunther	1996		53		min 5 yrs	67
Ohdera	2001	172	38	3	min 5 yrs	*Med: N/A; Lat: 89
Naudie	2004	113			11	90
Vince	2004		N/A		2-14 yrs	84-92
Berger	2005	59	3		min 10yrs	98
Verdonk	2005	87	11		2-14 yrs	* Med: 87; Lat: 73
Griffin	2007		N/A		2-17 yrs	85-95
Koskinen**	2007		N/A		1985-2003	53-81
Emerson Jr	2008	55			11.8	85
Geller	2008		N/A		min 5 yrs	82~98
Argenson	2008		40		min 10yrs	92

*: Does not have survivorship analysis, survival rate is revision rate.

Comparing to continuous interesting on UKA, reemphasizes of UKA nowadays might results partially with the development of minimally invasive surgical techniques (MIS) in the US

(Tanavalee & Yuktanandana, 2003; Tria Jr, 2002). A recent study summarized that long-term survivorship varied among various UKA from 84% with 22 years follow-up to 98% with 10 years follow-up (Geller, Yoon, & Macaulay, 2008), however another study among various type of UKA shows an estimated at 80% level (Koskinen, Paavolainen, Eskelinen, Pulkkinen, & Remes, 2007) at 10 years, which is not satisfied and controversial. This disagreement among studies might due to smaller subject numbers (less than 100), different techniques of surgeons and design concepts for different implants. It is also found that progression of OA in the opposite condyle (e.g., lateral condyle in MED-UKA) was at a slow rate by radiographic evidences (Barrett, 1987; Berger et al., 2005). Despite of the limited amount of long-term survivorship of UKA, current studies reveal that UKA has similar clinical outcome at pain recover and functional scores slightly higher than TKA, and range of motion (ROM) is reported even better than TKA (Griffin et al., 2007). It seems that UKA has a better survivorship and functional outcomes than decades, but loosening, wearing, and dislocation are still found. For example, the early failure rate (6~12 months) can be up to 38% of the femoral component (Mariani, Bourne, Jackson, Jackson, & Jones, 2007).

The low survivorship might be influenced by replacement design surgery techniques, design of replacement, progression of OA (Heck et al., 1993), and alignment of the knee (T.P Andriacchi, Stanwyck, & Galante, 1986). Surgical techniques play an important role on the performance of UKA. Surgical techniques can directly influence the post knee joint alignment. It has been suggested that limitations of preoperative deformity is varus 10 degrees and valgus 15 degrees (Tria Jr, 2002). Deformity higher than these limits potentially requires more ligament releases, and these releases are difficult in UKA and postoperative alignment is hard to maintain.

Preoperative malalignment of the knee joint will also cause abnormal loading on the ultra

high molecular weight polyethylene (UHMWPE) surface and cause unexpected wearing. Based on different preoperative alignment and diseased condyle, lateral or medial condyle of the knee will be replaced. Thus, different incision is required for MIS purpose to keep most soft tissues. It has been suggest that for MED-UKA, ligaments especially MCL should be reserved and not released (Tria Jr, 2002). On the other hand, in LAT-UKA, iliotibia band will be released due to the surgical incision. It is obvious that different preoperative alignment level (valgus or varus) will lead to different surgical approach and ligament releases. Consequently, it will potentially lead to different kinematics and kinetics maneuver of the knee joint.

Different replacement design is also one of the most direct factors, which affects clinical/functional performance and longterm survivorship biomechanically. For example, different curvature of the femoral condyle of the implant will affect the contact area and loading on the UHMWPE component, which lead to different loading and wearing pattern. Also, tibia component used in UKA has a less depth of stem compared to TKA due to MIS purpose. Thus, if there is any abnormal out-of plane motion occurred on the knee joint, it will cause higher abnormal loading on the tibia component and then cause wearing and loosening easier than TKA.

Furthermore, characteristics of replacing different component of the knee joint are not clear, particularly in person who replacing lateral component of the knee. Person who replaced the received LAT-UKA have mixed results compared with person who received MED-UKA on survivorship (Tanavalee & Yuktanandana, 2003). It was reported that LAT-UKA has 67% survival rate at 10 years (Gunther et al., 1996), but another study shows 89% with minimum 5 years follow-up (Odera, Tokunaga, & A., 2001). Theoretical speaking, MED-UKA and LAT-UKA should have similar outcomes since the goal of whether MED-UKA or LAT-UKA is to reconstruct back to normal knee functions. However, clinically LAT-UKA patients are

significantly less than MED-UKA, studies on MED- and LAT-UKA are rare, and lack of evidence to support assumption described. Consequently, knowledge on comparison between MED-UKA and LAT-UKA is essential to doctors to make proper decision for UKA candidates.

Clinical outcomes after UKA

Studies on clinical outcomes of UKA people have been documented. It was reported that clinical scores including pain level evaluated by visual analogue scale (VAS), Hospital for Special Surgery Score (HSS), patellar score (PS), and Knee Society Score (KSS) have no significant difference compared with bicondylar knee arthroplasty people (Fuchs et al., 2005) and significantly lower than healthy people (Fuchs et al., 2003). These scores are measured by both subjective feelings of patients such as pain and quality of life, and objective observations such as range of motion and stability. On the other hand, Short Form-36 (SF-36) health questionnaire results demonstrate that there is no significant difference on quality of life items but have significant differences on physical functions and pain (Fuchs et al., 2003). Results of clinical outcomes reveal that UKA has reconstructed the knee function to a better level than before, but do not fully explain why UKA has unsatisfied survivorship.

Importance of biomechanics and stair locomotion

Biomechanical information of UKA is critical to orthopaedic doctors, physical therapists and knee replacement designers to give patients better knee reconstruction. For instance, measuring the knee joint loading during different activities is important to not only help understanding forces on the knee joint but also contributes to knee replacement designs (D'Lima, Steklov, Fregly, Banks, & Colwell, 2008; Iesaka et al., 2002). Biomechanical approach has been

a main method to evaluate orthopaedic treatment and surgical performance, especially joint arthroplasty surgery (T. P. Andriacchi & Hurwitz, 1997). Motion analysis has been developed for decades, and has been a major method to evaluate functional activities (T. P. Andriacchi & Alexander, 2000).

Locomotion on stairs has been considered one of the most challenging and hazardous functional daily activities, especially for older people (Startzell, Owens, Mulfinger, & Cavanagh, 2000). Successful stair locomotion requires collaboration of cardiovascular system and musculoskeletal system with inputs from the somatosensory, visual and vestibular system. If any part of this cooperating system, difficulty of accomplish stair locomotion will increase. Failure of stair locomotion task, which mostly is falling, indicates increasing significant danger. Stair locomotion measured by motion analysis techniques was first studied by Andriacchi et al. (1980). Joint angles, joint moments and muscle firing pattern during stair ascent and descent were calculated. The knee joint flexion angle ranged approximately from 0 to 90 degrees during stair ascent and descent but significantly different pattern. The hip and the knee had significantly more joint moment but ankle didn't during stair ascent and descent comparing to level walking, which indicates the hip and knee played an important role to accomplish stair locomotion (T. P. Andriacchi et al., 1980). Muscles of the lower extremities transfer muscle energy into potential energy during stair ascent, and the potential energy has to be absorbed by the lower extremities muscles during stair descent (McFadyen & Winter, 1988; Riener, Rabuffetti, & Frigo, 2002). In normal individuals, knee joint and ankle joint play important role during stair locomotion to accomplish since greater joint power generation and absorption were observed (McFadyen & Winter, 1988; Riener et al., 2002). From empirical observation, trunk movement during stair locomotion in healthy individual is normally kept erected and stable. It is supposed that the knee

and hip joint is critical to accomplish stair locomotion and the hip joint is also important to keep upper body stable. However, it has still not been fully discussed (T. P. Andriacchi et al., 1980; McFadyen & Winter, 1988; Riener et al., 2002).

Stair ascent and descent in TKA individuals were studied as much as normal population (T. P. Andriacchi, Galante, & Fermier, 1982; Catani et al., 2003; Dorr, Ochsner, Gronley, & Perry, 1988; Kelman, Biden, Wyatt, Ritter, & Colwell Jr, 1989), but there was only one study on UKA population discussed about early design of UKA (Weinstein, Andriacchi, & Galante, 1986). Differences among implants designs are more obvious under more stressful stair activity (T. P. Andriacchi et al., 1982). Despite of differences of TKA designs (e.g. posterior stabilized and crucial ligament retaining), modern TKA knees represent both different kinematic and kinetic patterns compared to healthy individuals (Catani et al., 2003) during stair climbing. UKA biomechanics was studied by Weinstein and colleagues (1986) during walking and stair climbing. Although design of implant is quite different from modern one and limited by small amount of participant, results indicate that most UKA individuals (11 of 12 knees) with their medial condyle replaced have no difference on maximum flexion angle during stairs activities but the adduction moment strong correlation with postoperative alignment. This finding might indicate the failure of UKA is due to alignment biomechanically. Overall, stair locomotion in UKA individual is not clear, especially stair descending. It is essential to investigate biomechanics of UKA individuals during stair locomotion, and thus allows making suggestion to orthopaedic doctors, physical therapist, and knee replacement designers.

Medical imaging measurements and videofluoroscopy techniques

Besides stereophotogrammetry method, kinematic measurement through medical images is

another popular approach. The bones and implants can be clearly identified and there is no skin movement artefact involved using medical imaging approach, which is a major error source on marker based measurement. Thus, joint kinematics measurement using medical images especially x-ray is widely used. With the digitization of medical images (James, Davies, Cowen, & O'Connor, 2001), medical image storage and analysis become more convenient.

Kinematics measurement via fluoroscopy is a better approach than traditional single plane x-ray measurement. Fluoroscopy provides a series of images which consists continuous measurement under x-ray exposure. Modern image-intensifier-based digital fluoroscopy system converts invisible x-ray into visible lights and forms image on phosphor screen. However, image will distort by magnetic field of the earth and point projection effects. Thus, image correction is necessary for all subsequent analysis using fluoroscopy system. For example, polynomial function is used to correct image distortion by Baltzopoulos and a video-fluoroscopic measurement is conducted to measure the patella tendon moment arm and angle of tibia plane during knee joint flexion/extension motion (Baltzopoulos, 1995). This approach is a good kinematic measurement but still limited in two dimensional (2D). In addition, field of view (FOV) of fluoroscopy machine and radiation dosage will affect quality of images and limit its application.

Roentgen stereophotogrammetry analysis (RSA) is a three dimensional (3D) measurement for skeletal kinematics with high accuracy of 10-250 μm in translation and 0.03-0.6 degrees in rotation (Selvik, 1989). However, RSA has much higher radiation exposure than other x-ray measurements, and it is a 3D static measurement (Baltzopoulos, 1995). Although dynamic measurement is possible by using film exchanger, RSA limits joint movement due to limited space caused by biplane setup. Thus RSA is not an adequate measurement for lower extremity

kinematics.

A modern 3D kinematic measurement using fluoroscopy was first proposed by Banks (Banks, 1992) and applied on TKA 3D kinematics studies (Banks & Hodge, 1996) with high accuracy (0.5 mm in translation and 0.5 degrees in rotation). He combined computer-assisted design (CAD) model and dynamic fluoroscopic images recorded by video system to describe accurate *in vivo* implant motion of TKA by image registering techniques. With a image bank consisting of implant silhouettes at different position and orientation described by Fourier descriptor (Wallace & Mitchell Owen, 1980; Wallace & Wintz, 1980), 3D kinematics of knee implant could quickly and accurately be calculated. This method was then caught other researchers interests and applied in TKA kinematic studies (Dennis et al., 1998; Hoff, Komistek, Dennis, Gabriel, & Walker, 1998; Leardini et al., 2005; Stiehl, Dennis, Komistek, & Keblish, 1997; Zuffi, Leardini, Catani, Fantozzi, & Cappello, 1999) and recently healthy knee joint kinematics (Lu, Tsai, Kuo, Hsu, & Chen, 2008).

Biomechanical functional performance after UKA

Theoretically UKA should reveal better kinematic outcome then TKA since UKA keeps more knee natural anatomical structures. The following section will briefly review biomechanical functional performances after receiving UKA on typical functional activities.

Gait analysis on UKA individuals

Limited gait analysis has been investigated in UKA patients (Fuchs et al., 2005; Fuchs et al., 2003; Webster, Wittwer, & Feller, 2003). Results show that UKA has lower vertical ground reaction force (VGRF) and different muscle activations compared with healthy individuals (Fuchs et al., 2005; Fuchs et al., 2003), which implies UKA might fail to reconstruct normal function. Another study shows that knee joint kinematics on the sagittal plane has been restored

(Webster et al., 2003), however, how the knee moves out-of-plane is still not reported. It indicates that UKA is potentially sufficient. Generally studies show improved functional outcomes but biomechanical results remain controversy. But these clinical and functional assessments do not fully explain why UKA has lower survivorship although recovery is good, especially long-term survivorship. Different demographic distribution of patients, pre- and post-alignments, and different surgical approach (lateral and medial) has not been fully discussed. In addition, how UKA affect the hip and ankle joints during functional activities, especially in high demand ones, has not been discovered.

Overall, UKA has better survivorship and post-surgery outcomes than years ago. However, it is still not satisfied on the literature. In addition, it is not clear that if UKA individuals really yield functional outcomes as expected compared to healthy individuals. Also comparing to healthy knee biomechanics, it is also not sure that if the LAT-UKA and MED-UKA knees act similar to healthy ones.

Videofluoroscopy measurement on UKA individuals

Videofluoroscopy measurement has been applied on comparing uniconpartmental and bicompartamental knee replacements during treadmill gait, stair stepping, and lounge (Banks, Fregly, Boniforti, Reinschmidt, & Romagnoli, 2005). It has found that MED-UKA demonstrate greater posterior translation than healthy knee (Hill et al., 2000; Iwaki, Pinskerova, & Freeman, 2000) during stair stepping, which might indicate why UKA has lower survivorship due to laxity of the joint. Videofluoroscopy method is a sufficient measurement to help understanding biomechanical maneuver of UKA. However, lack of kinetics limits interpreting via videofluoroscopy method. Consequently, it is essential to have both videofluoroscopy and stereophotogrammetry approaches on UKA patients to have better understanding.

Summary

Knee arthroplasty is a main choice of treatment aims to remove pain and restore knee functions for severe OA patients. Patients who undergo UKA can expect reconstructed functional ability but survivorship remains controversial, and restored knee function is potentially still impaired when comparing with healthy adults according to limited studies. How preoperative alignment affects postoperative outcomes is unclear. It is expected to be different due to different surgical approaches and ligament releases. In addition, research on UKA individuals has focused on gait and clinical outcomes, functional activities such as sit-to-stand, stand-to-sit, and stair ascent/descent are not thoroughly discussed. Consequently, it is important to have a better understanding of the differences between MED- and LAT-UKA individual, and compared to healthy individuals.

CHAPTER 3

VIDEOFLUOROSCOPIC COMPARISON OF THE KNEE JOINT KINEMATICS EXHIBITED
DURING A STEP-UP MANEUVER OF MED- AND LAT-UKA INDIVIDUALS¹

¹ Yang-Chieh Fu, Ormonde M. Mahoney, Scott A. Banks, Tracy L. Kinsey, and Kathy J. Simpson. To be submitted to *Journal of Bone and Joint Surgery, American Volume*.

Abstract

Background: Evidence of unicompartmental knee arthroplasty (UKA) efficacy varies, and reasons for this phenomenon are not clear. Biomechanically, knee joint kinematics is one of the most direct factors affecting clinical and other physical function performance and long-term survivorship. The goal of the study was to compare the *in-vivo* and tibio-femoral bones and implant kinematics of lateral (LAT) and medial (MED) UKA users who performed a step-up motion.

Methods: Fourteen MED-UKA and eight LAT-UKA participants (respectively, age: 68.6 ± 7.1 yrs, 62.8 ± 7.9 yrs; ht: 162.7 ± 7.8 cm, 166.1 ± 7.1 cm; mass: 73.8 ± 12.7 kg, 70.1 ± 12.7 kg;), pre-operative knee varus range: 10° valgus to 7° varus were recruited for this study from an orthopedic clinic's research database. Each UKA participant first underwent a computed tomography of the operated knee, and then performed a step-up task onto a box with UKA limb at a self-selected natural speed. The motion was recorded by a modified-videofluoroscopy system (digital video camera at 30 fps and fluoroscopic instrument). Image reconstruction of the tibio-femoral positions from the fluoroscopic images involved image registration using a hybrid knee model reconstructed from the CT scan images and the manufacturer's implant CAD models. Joint angles and linear contact trajectories of the medial and lateral condyles of the UKA knees were calculated after. Angular and linear displacement variables were compared statistically between LAT- and MED- UKA group using one-way ANOVA. ($\alpha = 0.05$).

Results: No significant difference was found between groups for any variable. The MED-UKA group demonstrated $11.4 \pm 6.6^\circ$ maximum knee joint internal/external rotation displacement and $6.1 \pm 2.3^\circ$ maximum joint abduction/adduction displacements. LAT-UKA group had $6.5 \pm 3.6^\circ$ internal/external rotation and $4.7 \pm 1.6^\circ$ of abduction/adduction displacement.

MED-UKA exhibited posterior translation 10.6 ± 8.8 mm on the medial condyle and 13.2 ± 6.9 mm on the lateral condyle. LAT-UKA exhibited posterior translation 13.8 ± 6.0 mm on the medial and 9.7 ± 7.7 mm on the lateral.

Results: The MED-UKA group, demonstrated, respectively, $11.4 \pm 6.6^\circ$ maximum knee joint internal/external rotation displacement and $6.1 \pm 2.3^\circ$ maximum joint abduction/adduction displacements. LAT-UKA group had $6.5 \pm 3.6^\circ$ internal/external rotation and $4.7 \pm 1.6^\circ$ of abduction/adduction displacement. MED-UKA exhibited posterior translation 10.6 ± 8.8 mm on the medial condyle and 13.2 ± 6.9 mm on the lateral condyle. LAT-UKA exhibited posterior translation 13.8 ± 6.0 mm on the medial and 9.7 ± 7.7 mm on the lateral. No significant differences were found between groups on those variables.

Conclusion: Both MED- and LAT-UKA individuals demonstrated well-reconstructed joint kinematics although posterior translations were greater than healthy knee's in the literature. The results may be helpful for doctors to construct a better surgical plan and important to implant designers to improve current unicompartmental implants.

Level of Evidence: Therapeutic Level IV.

Keywords: videofluoroscopy, joint kinematics, tibio-femoral contact point trajectories

Introduction

With the number of older adults increases globally, the number of people who will develop osteoarthritis (OA) will also increase ¹⁵. It is estimated that approximately 10% of the world population who are 60+ years old have symptomatic problems caused by OA ³⁴. In 2005, it was reported that the U.S.A. has an estimated 26.9 million adults with OA, an increase of 1.8 million people from 1990 ²⁰. Moreover, the number of people who have OA in the U.S.A. will be nearly 67 million by 2030 ¹⁵.

With the increased number of future individuals who will seek solutions for painful knee OA, it is important to have several, evidence-based alternatives available so the best treatment for a given individual can be selected. Among various treatments for OA, modern unicompartmental knee arthroplasty (UKA) has been considered a good treatment due to improved implant design and minimally invasive surgical techniques. Compared to a total knee arthroplasty (TKA), a UKA has smaller incision, less hospital time, more intact soft tissues such as anterior cruciate ligament (ACL), and less postoperative pain ²⁶. Previous studies have shown that UKA has similar or slightly better clinical evaluation outcomes (e.g. Hospital for Special Surgery knee score) ^{9,24,35} and knee flexion/extension range of motion ^{11,19}. Although UKAs have good outcomes, the survival rate at 10 years for current UKAs varies from 67% to 98% ^{7,10,11,18,23,27,35,36}, which is inconsistent compared to modern TKA that has at least 90% survival rate at 10 years¹¹. Furthermore if split by compartment, reported survival rates for LAT-UKA range from 67% to 92% ^{12,23}, which implies LAT-UKA might be worse than MED-UKA that has 92% survival rate ².

The inconsistent survival rate of UKA implies there may be room for improvement, and reason for the phenomenon is still unclear. Post-operatively, for individuals who have had a UKA, knee joint kinematics direct affect and indirectly reflect the biomechanics that underlie some of

the clinical and functional outcomes and long-term survivorship^{13,25}. Improper knee kinematics and malalignment may be important biomechanical factors lead to progression of OA and/or failure of UKA^{25,30}. The healthy compartment of the knee joint may change its kinematics after UKA, which may cause unexpected excessive loading and progress OA. Unfortunately, the lower extremity kinematics of today's UKA patients, especially of LAT-UKA is limited¹⁰.

Besides limited overall understanding of UKA, knowledge on LAT-UKA is very limited and differences between LAT- and MED-UKA also lacked. The medial and lateral condyle of the femur are different in anatomy and biomechanical behaviors^{14,16}, which means biomechanics of them are different. However, most studies to date focused on MED-UKA only, or mixed LAT- and MED-UKA together^{7,10,11,18,27,35,36}.

Videofluoroscopy is a technique used to capture *in-vivo* locations of articulating bone and implant structures to later reconstruct knee joint kinematics accurately^{1,4,8,22}. Until recently, this methodology had been developed and applied to kinematic investigation of TKA^{4,6,21,38}, but valid image registration techniques now exist for healthy knee joint kinematics studies²² and UKA^{1,3}. In videofluoroscopy study of UKA, it was found that the medial component of the MED-UKA demonstrate greater posterior translation than the health knee during stair stepping³. Although detail knee motion of UKA has been studied, evidence for the inconsistent survival rate is still limited. One possible reason would be the motion for the healthy compartment after UKA has not been explored yet, and it seems to be an important piece of evidence, to help to clarify if the inconsistent survival rate is due to inadequate kinematics of healthy and/or implant compartment.

Thus, the goal of the study was to compare between the operated limbs of LAT- and MED-UKA users the *in-vivo*, 3-D motion and linear contact trajectory of both medial and lateral condyles displayed during a step-up motion of step-up task, using videofluoroscopy. Because the

medial and lateral condyle of the femur are different anatomically and biomechanically^{14,16}, it was hypothesized that the MED-UKA group compared to the LAT-UKA group would exhibit greater anterior-posterior (AP) translation at the medial condyle and less AP translation at the lateral condyle, and less internal rotation displacement and abduction displacement of the knee joint.

Methods

Participants

Fourteen unilateral MED-UKA (5 males and 9 females; age: 68.6 ± 7.1 yrs; ht: 162.7 ± 7.8 cm; mass: 73.8 ± 12.7 kg,) and eight LAT-UKA (2 males and 6 females; age: 62.8 ± 7.9 yrs; ht: 166.1 ± 7.1 cm; mass: 70.1 ± 12.7 kg,) participants with post-op knee joint varus/valgus values ranging from 10° valgus to 7° varus were recruited for this study. All participants received a UKA (Align 360[®] Unicompartmental Knee System; Cardo[™] Medical, CA) from a patient research database of one of the authors (OMM from the Athens Orthopedic Clinic) at least 6 months prior to testing. A participant who had an implant in any other lower limb joint or any medical condition or injury that could potentially affect the participant's movements or safety was excluded from this study. All participants provided written informed consent. The research study was approved by the Human Subject Institutional Review Boards (see Appendix A) of all participating organizations.

Protocol

All participants completed a health and physical activity questionnaire (Appendix A) before participating to confirm if their health status qualified them for the study and to ascertain their level of daily physical function. Each UKA participant first received a computed tomography (CT,

Aquilion64™, Toshiba, Japan) of the operated leg to reconstruct bone and implant models of a UKA knee. The longitudinal range of the scanned region was 30 cm, that is, 15 cm superior to 15 cm inferior from the centerline of the knee joint. Pixel size for each transaction image was 0.42 mm x 0.42 mm and the interval between cross-sectional slices was 1 mm.

Next, for the videofluoroscopy testing, the task was to perform a step-up task. While wearing a lead vest, the participant started movement with the bare foot of the UKA limb on a 20 cm high step box with the tibia perpendicular to the step box and the UKA limb parallel to the phosphor screen of the fluoroscopy machine. The participant then raised the body upwards by extending the UKA limb, holding this position for about one to two s, and then returning to the original position. The participant performed the step up-and-down task three times, at a self-selected natural speed with at least 30 s rest provided between each repetition. A C-arm type videofluoroscopy system (OEC-Diasonics 9400™, General Electric, USA) with a digital-video camera (DMK 31AF03™, The Imaging Source LLC, USA) was used to capture (632 x 680 pixels; 30 fps) the sagittal plane view of the UKA knee joint region during each repetition. An image of a calibration object was captured to later correct image distortion and scale image size ⁴.

Data Analysis

The procedures described below were used to reconstruct the kinematics of the knee during step-up motion (Figure 3.1). For each participant, geometric models of the femur and the tibia were first segmented and reconstructed from the CT transactional serial images using ITK-Snap ³⁷ (Version 1.8.0, www.itksnap.org). The initial contour of the target bone for each CT transactional image was segmented automatically by adjusting grayscale threshold. Due to distortion caused by the metal compartment of the implant, contours near the implant were segmented manually. Then, the target-bone model was reconstructed based on the selected

contours. The geometric models of the UKA implants also were segmented and reconstructed using the same procedure. The reconstructed UKA models were used to determine the spatial relationship between the implant and the adjacent bone (e.g. UKA femoral component corresponded to the femur).

Next, the reconstructed geometric models of the bones and implants from the CT data were then used to generate a hybrid geometric segment model. The hybrid model was generated by merging the CT bone model and computer-aided-designed (CAD) model of the implant using GeoMagic Studio[®] 4.1.1 (Geomagic, Inc, USA)³. The CAD model, provided by the manufacturer, was oriented and fit to the location of the CT scanned implant model via the optimization protocol provide by GeoMagic Studio, and then replaced the scanned implant model to form the hybrid model. Axis directions of the hybrid CAD models were defined as: +x = posterior, +y = superior, and +z= medial^{3,22}.

Fluoroscopic images from the step-up phase of one trial of the step-up-down task were then processed (JointTrack, version 2.0.2, University of Florida)^{3,4}. First, distortions of videofluoroscopic images were corrected³⁸. Then registration was performed, based on optimization techniques using nonlinear, least-squares algorithms to find the best match in orientation between the outline of the models and bone/implant contours³. The fluoroscopic contours were detected using Canny method⁵.

Knee joint kinematics were generated using an in-house MATLAB program (MATLAB[®] 7.0, the Mathworks, Inc. US). After filtering the registered data (Butterworth 4th order low-pass filter, 2 Hz cutoff) to remove registration noise, Cardan angles of the knee joint were calculated and expressed as the orientations of the tibia's segmental axes relative to those of the femur^{3,22}. Due to all participants do not demonstrate the same range of motion of knee flexion, all

kinematic variables were shifted to his/her reference point while the knee was at 30° flexion due to various range of motion among all participants.

The displacements of the contact points of the lateral and medial femoral condyles on the corresponding tibial plateau (the femur relative to the tibia) were used to describe the linear surface kinematics. First, an estimated AP translation line on the tibial plane was selected semi-manually with computer graphic assistance. For each participant, one point on the middle of healthy anterior tibial plateau edge and one on the middle of the posterior edge, and same two points on the anterior and posterior edge of the tibial tray were selected manually. The minimum intra-class correlation (ICC(2, k)) of identifying these points was greater than 0.96, the and maximum standard error of measurement (SEM) was 0.68 mm³¹. Next, the tibio-femoral contact point for each plateau/condyle was defined as the closest inferior point of the femoral condyle projected onto the corresponding AP translation line. The contact point for a given pose was then calculated by the projected femur point onto the AP translation line.

Statistical analysis

To determine kinematic differences between the UKA groups, all dependent variables were tested using one-way ANOVA (SPSS® Version 18.0; SPSS Inc., Chicago, USA). Tested variables were maximum AP translations of the medial and lateral tibio-femoral contact points; maximum internal rotation abduction displacements occurring between the knee flexion angles of 10° and 60°. The significance level was set at $\alpha = 0.05$. *P* values between 0.06 and 0.10 were considered to be close to significance, indicating a potential tendency toward a group difference. Effect sizes (partial η^2) for each dependent variable were reported.

Results

As shown in Figure 3.2 for angular displacements, for the step-up phase when the knee was extending between the knee angles of 10° and 60°, the MED-UKA knee joint exhibited adduction and external rotation displacement while the LAT-UKA group exhibited opposite direction. No statistical differences was displayed for knee joint internal rotation ($p = 0.065$) and abduction ($p = 0.146$), and as the means varied by about 5° and 1.5° respectively. The MED-UKA ($X \pm SD$: $11.4 \pm 6.6^\circ$) had a nonsignificant tendency ($p = 0.065$) to have greater knee internal rotation displacement than the LAT-UKA group ($6.5 \pm 3.6^\circ$).

There also was no significant difference between posterior translation of MED- and LAT-UKA groups. Figure 3.3 shows the tibio-femoral contact point patterns of a representative MED-UKA and LAT-UKA participant, while the ensemble patterns of the contact points trajectories of the both UKA groups are shown in Figure 3.4. Interestingly, for posterior translation of the femur relative to the tibia, the MED-UKA compared to the LAT-UKA group displayed a tendency of less-posterior translation of the medial condyle of the femur relative to tibia, but a tendency of greater femoral condyle translation at 25° knee flex and 40° to 60° knee flex. MED-UKA exhibited maximum posterior translation 10.6 ± 8.83 mm on the medial condyle and 13.2 ± 6.86 mm on the lateral condyle (Table 3.1). LAT-UKA exhibited maximum posterior translation 13.8 ± 6.00 mm on the medial and 9.7 ± 7.74 mm on the lateral.

Discussion

The current study provides a comparison of knee kinematics during step-up movement between MED- and LAT-UKA individuals, and kinematics of healthy compartment of UKA knees were also investigated. Results did not support predictions due to lack of significant

differences. It might indicate that the knee joint kinematics of both MED- and LAT-UKA individuals were reconstructed after receiving UKA, compared with healthy and TKA individuals in the literature.

No significant difference has been found between joint kinematics and A-P translations (Table 3.1). Maximum posterior translations of MED- and LAT-UKA groups are consistent with previous studies in cadaver or *in-vivo* healthy knees^{14,16,22,33} but greater than studies on UKA knees^{1,3} and TKA knees^{17,32}. The LAT-UKA group was prone to have less internal rotation than MED-UKA group ($p = 0.065$) with small effect size (partial $\eta^2 = 0.16$). Behaviorally, it might imply that the LAT-UKA individuals do not display enough internal rotation compared to MED-UKA individuals that the purpose of implant design aims to accomplish.

Posterior translations of both medial and lateral condyles were observed in both MED- and LAT-UKA groups (Figure 3.3 and 3.4). Maximum posterior translations of MED- and LAT-UKA groups are consistent with previous studies in cadaver or *in-vivo* healthy knees^{14,16,22,33} but greater than studies on UKA knees^{1,3} and TKA knees^{17,32}. Most of the posterior translations were achieved around 30° knee flexion in both MED and LAT groups.

Although no significant differences were found, the MED-UKA group was tended to have greater lateral condyle movement than the medial, which is consistent with previous studies demonstrated in healthy knee joint^{14,16,22}. However, the LAT-UKA group demonstrated less lateral condyle movement than the medial, which conflicts with literature reports. The surrounding soft tissues around the replaced compartment might become tight after surgery. In a healthy knee, the lateral condyle functions for mobility (more translation) and medial condyle is for stability (less translation)^{14,16}. Thus, this tightness of soft tissues functions positive in medial condyle but negative in lateral condyle.

Qualitatively, the kinematic patterns were consistent with previous studies. We found that contact point movements of the healthy knee condyle in both MED- and LAT-UKA groups were fluctuating compared to the implant side. This might be due to the changing geometry of the femoral condyle caused by degeneration and/or the unexpected bone growth.

Compared to literature^{1,3,22}, greater posterior translations in both groups might indicate that the UKA knee might have greater joint laxity. It has been suggested that joint laxity is an important biomechanical factor that could cause progression of OA^{28,29}. Inadequate kinematics in a lax knee could cause unexpected loading at the knee joint during motion, thus it might reduce life of implant or progress OA and a revision is needed eventually. Although this phenomenon might link to the inconsistency of UKA survival rates^{7,10,11,18,27,35,36}, evidence of current study was insufficient to prove and explain this link.

Both UKA groups demonstrated different knee kinematics patterns. Compared to healthy knee kinematic patterns²², the MED-UKA group had an averaged inverse pattern in abduction/adduction and LAT-UKA group had an averaged inverse pattern in internal/external rotation (Figure 3.2). This might be due to different loading condition between current study (weight bearing step-up task) and previous study (active knee flexion with 5 lb loading at the ankle)²². In our study, UKA individuals require sufficient strength to raise the whole body mass to accomplish step-up motion. UKA individuals generally have weaker muscle strengths due to age. Thus, UKA individuals might have insufficient muscle strength that cause the knee joint kinematics does not follow a typical pattern.

Our findings are limited by small sampling size. A *post-hoc* power analysis showed that it requires at least 23 subjects per group to detect joint kinematics differences, and at least 73 per group to detect posterior translation differences. Considering for feasibility of recruiting

participants, a feasible sample size for the study would be 20 per group. Both MED- and LAT-UKA groups are below 20, which means there are some chance for Type II error. Quality of fluoroscopic images also significantly influences kinematics outcomes. It is difficult to adjust the contrast of fluoroscopic images to allow both bone and metal component have good contours. Furthermore, true orientation and translation between implant and bone of the hybrid model is unknown, due to the distorted CT images close to implants. Although an estimated orientation and translation between implant and bone component can be determined by manually reconstructing CT models, small offset might cause mismatch during image match process.

In conclusion, *in-vivo* 3D knee joint and surface kinematics during step-up motion in both MED- and LAT-UKA individuals were measured using videofluoroscopy method with hybrid models. Both MED- and LAT-UKA individuals demonstrated well-reconstructed joint kinematics and were close to previous studies. No significant difference was found between MED- and LAT-UKA groups. The results may be helpful for doctors to construct a better surgical plan and important to implant designer to improve current unicompartmental implant design.

Conflict of interest

There is no conflict of interest.

Acknowledgements

The study was supported by Athens Orthopedic Clinic Foundation, USA. The authors thank Megan Johnson for her assistance with recruiting participants. The authors thank Athens Orthopedic Clinic and St. Mary's hospital staffs for their assistance with data collection.

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Table

Table 3.1. Summary of comparisons between medial UKA and lateral UKA groups for maximum internal rotation (INT) joint displacement, abduction (ABD) joint displacement, and maximum posterior contact displacements of medial (Med- Post) and lateral (Lat- Post) condyles during step-up motion.

Mean $\pm$ SD	MED-UKA	LAT-UKA	<i>p</i> value	partial η^2
INT (°)	11.4 $\pm$ 6.6	6.5 $\pm$ 3.6	0.065	0.16
ABD (°)	6.1 $\pm$ 2.3	4.7 $\pm$ 1.6	0.146	0.10
Med-Post (mm)	10.6 $\pm$ 8.8	13.8 $\pm$ 6.0	0.386	0.04
Lat-Post (mm)	13.2 $\pm$ 6.9	9.7 $\pm$ 7.7	0.285	0.06

Figures

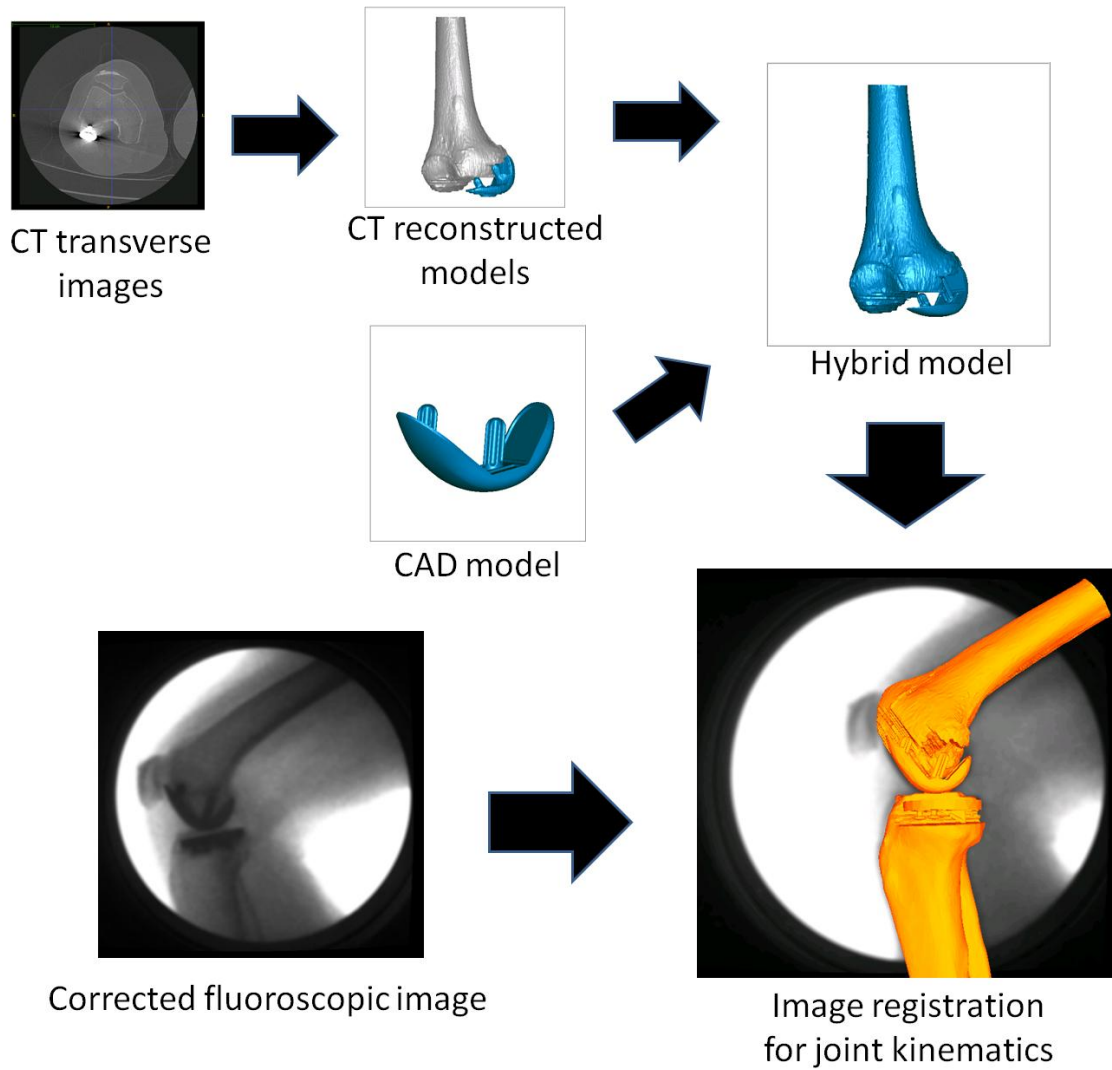


Figure 3.1 Data analysis flow chart for knee joint kinematics reconstruction. The reconstructed CT scan models including bone and implant are merged with a computer-aided designed (CAD) model to obtain a hybrid model for analysis. The joint kinematics during step-up task were reconstructed by registering the hybrid model on to a series of corrected fluoroscopic images.

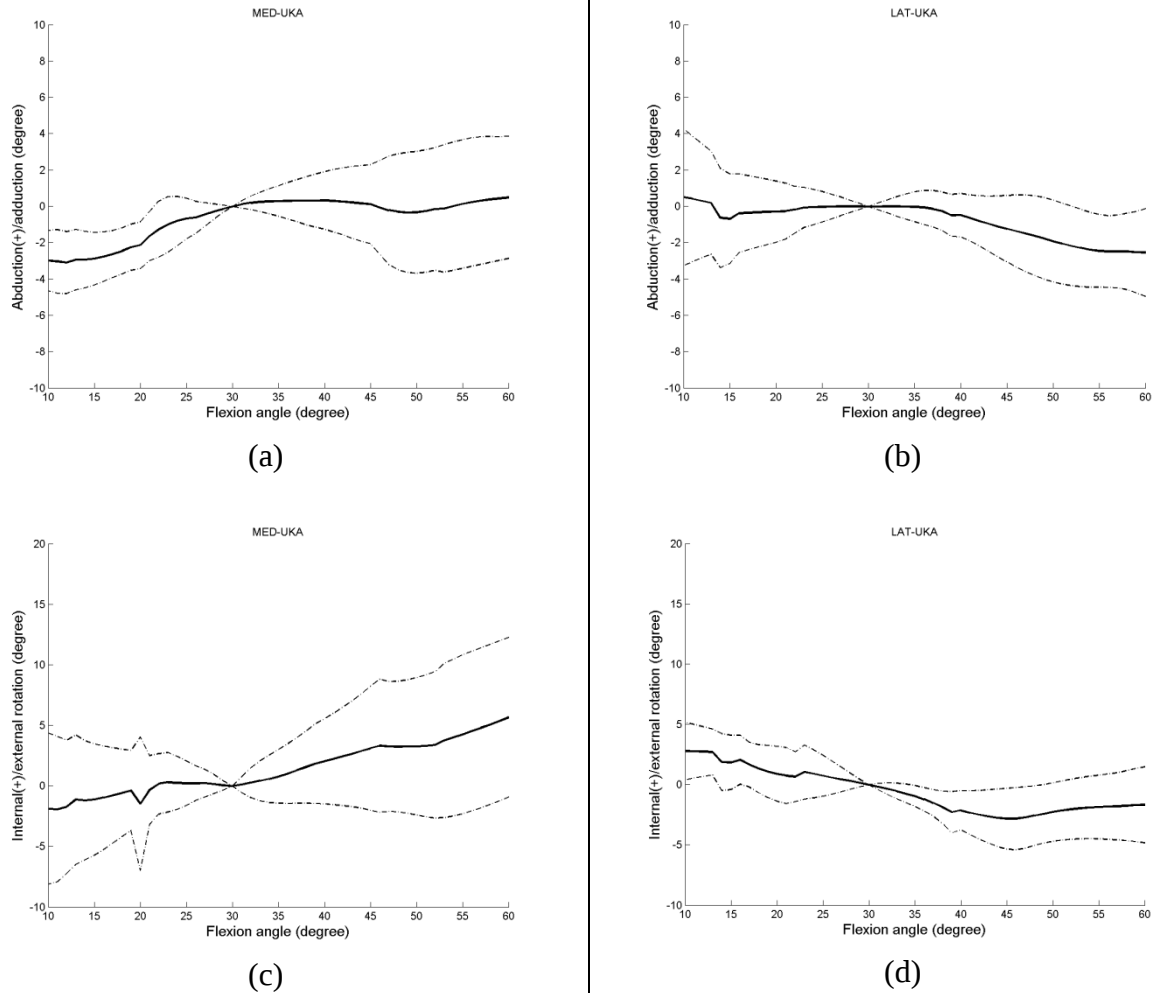
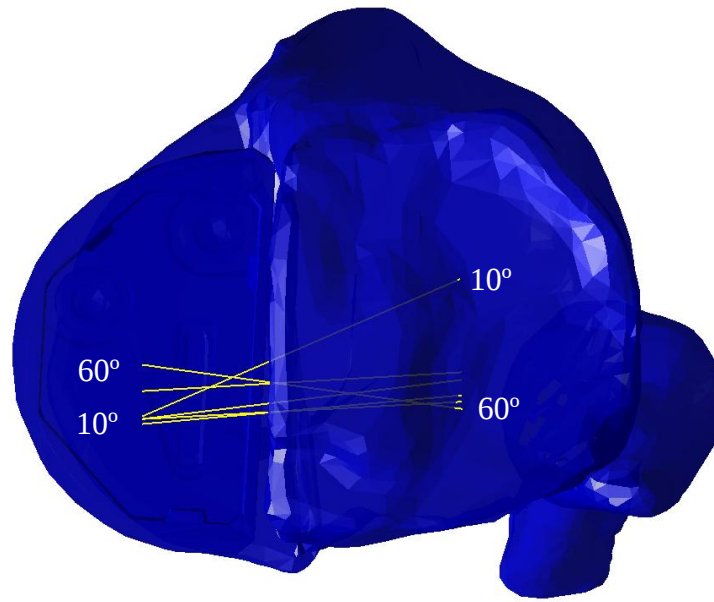
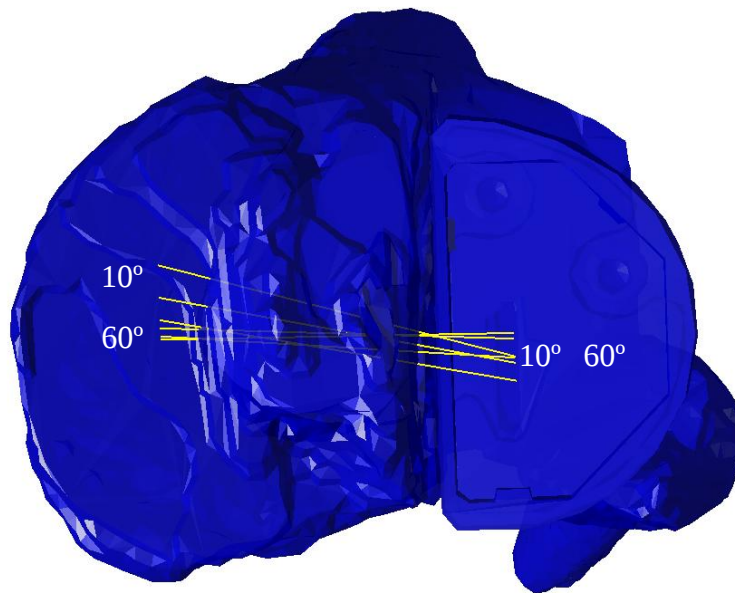


Figure 3.2 Ensemble joint angles (solid line) and one standard deviation from the mean curve (dashed line) for medial (MED) and lateral (LAT) UKA groups, respectively: abduction/adduction (a, b) internal-external rotation (c, d) during the step-up phase. Results are scaled to 30° flexion.

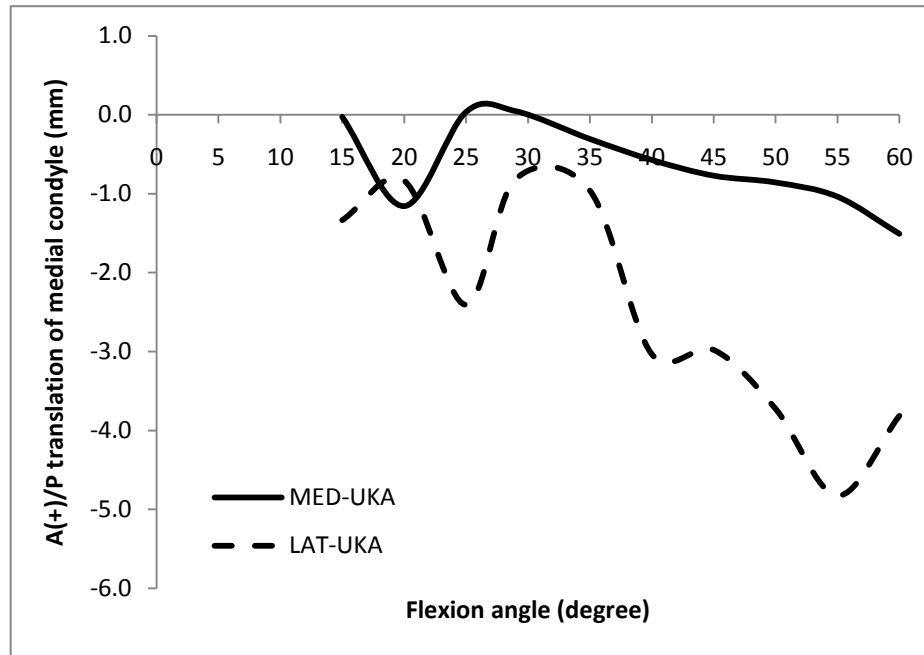


(a)

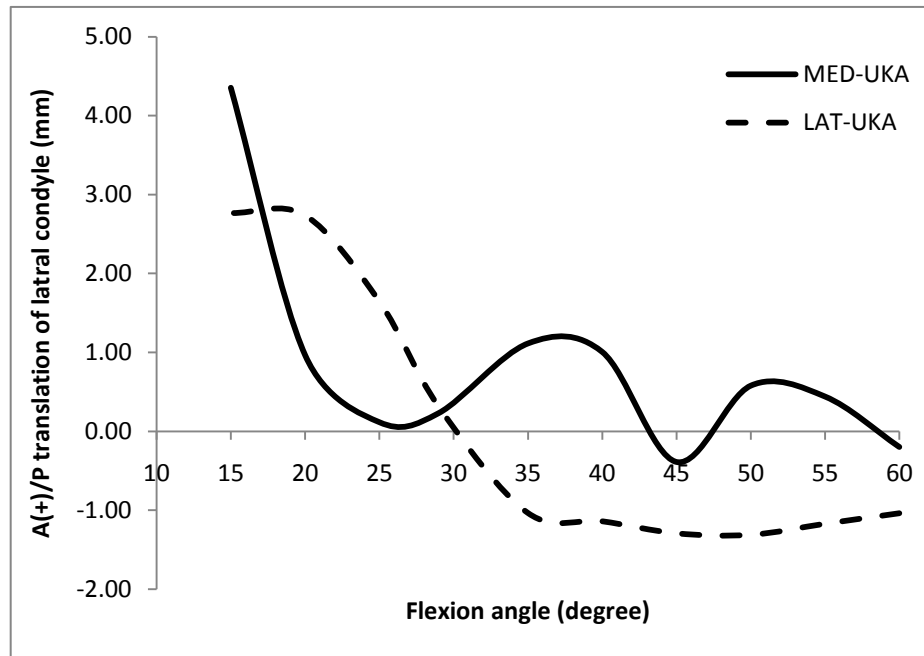


(b)

Figure 3.3 Example of contact trajectories from flexion 10° to 60° for a particular participant of
 a) Medial UKA b) lateral UKA.



(a)



(b)

Figure 3.4 Ensemble anterior-posterior translation of tibiofemoral contact points for the a) medial and b) lateral condyle of MED-UKA (solid line) and LAT-UKA (dash line).

CHAPTER 4

BIOMECHANICS OF MEDIAL AND LATERAL UNICOMPARTMENTAL KNEE
ARTHROPLASTY INDIVIDUALS DURING STAIR ASCENT¹

¹ Yang-Chieh Fu, Ormonde M. Mahoney, Jae Pom Yom, Tracy L. Kinsey, Cathleen Brown and Kathy J. Simpson.
To be submitted to *Gait and Posture*.

Abstract

Unicompartmental knee arthroplasty (UKA) is a partial joint replacement procedure, in which only the most damaged tibio-femoral compartment is replaced, either the medial (MED-UKA) or lateral condyle (LAT-UKA). However, the biomechanics of UKA limbs are not well understood, particularly for LAT-UKA individuals. The purpose of the study was to investigate the influence of a UKA on kinematics and kinetics displayed during stair ascent by MED- and LAT-UKA individuals as compared to equivalent, healthy controls (MED-CON and LAT-CON, respectively). A total of 26 UKA participants (17 MED-UKA and 9 LAT-UKA) and 26 matched healthy individuals were recruited for the study. All participants performed 5 trials of ascending 3 steps (height: 20 cm; depth: 28 cm) with a force platform embedded in the 1st step. Kinematics and kinetics of one stair stride were compared between the UKA limb of UKA groups and the matched limb of the corresponding CON groups using paired t-tests. The MED-UKA group had approximately 5° less maximum knee extension displacement than MED-CON group ($p = 0.022$, Cohen's $d = 0.14$), and the LAT-UKA group had 5° greater maximum hip abduction than LAT-CON during stance phase ($p = 0.041$, Cohen's $d = 0.89$). No other statistical significance was found for other kinematic or kinetic variables. Two different knee joint moment patterns for all planes were displayed among the participants; however, the patterns were not associated with UKA implant type. Current results showed that both MED- and LAT- UKA display similar kinematics and kinetics compared to healthy knees. These data provide support for using a UKA, when appropriate, for severe OA treatment.

Keywords: Stair locomotion; Kinematics; Kinetics; Motion analysis; unicompartmental knee replacement

Introduction

Unicompartmental knee arthroplasty (UKA) is a surgical procedure for osteoarthritis (OA), during which only the damaged tibio-femoral compartment is replaced, either the medial (MED) or lateral (LAT) compartment. Although UKA individuals have good functional outcomes (e.g., increased Hospital for Special Surgery knee scores from TKA's) [1-3], the survival rate at 10 years for current UKAs has varied from 73% to 98% [3-7]. Moreover, the 5 to 10 year survival rate of LAT-UKA (range: 67 to 92% [8-10]) compared to MED-TKA (92% 10 years survivor rate [11]) tends to be lower. Use of UKA also is still controversial among surgeons [12].

Many factors contribute to survival rate, and understanding the mechanics involved in daily activities and their effects on knee joint loading and movement are crucial. Improper knee kinematics are one potential biomechanical factor implicated in the progression of OA in the healthy condyle of the UKA knee [13, 14]. However, knowledge of knee joint biomechanics of UKA patients for functional tasks, especially of LAT-UKA, is limited [4]. Most UKA biomechanics and other outcome studies focus only on data of MED-UKA individuals, or do not distinguish between LAT- and MED-UKA individuals' data [3-7, 15, 16].

Although some is known about the kinematics of gait of UKA, little is known about kinematics and kinetics of stair ascent. Gait analysis results show that MED-UKA individuals have well-reconstructed knee joint kinematics about the flex/extension axis compared to their contralateral limb [17] or healthy individuals [1]. Although these studies imply UKA reconstruct sagittal plane knee kinematics satisfactorily, knee motions about the other axes and kinetics are unknown, nor are the mechanics that occur during other functional activities understood.

Stair ascent is a muscularly-demanding [18], and important task often used in daily life. The kinematics and kinetics of the knee joint are very important to accomplishing stair

locomotion [19]. However, there is only one biomechanical UKA investigation of stair ascent to date [20]. Weinstein [20] determined, in 1986, that most MED-UKA individuals (11 of 12 knees) compared to 14 healthy older adults displayed no difference for maximum knee flexion angle. However, no ab/adduction or int/external rotation kinematics or any joint kinetics were reported. Additionally, UKA technology and surgical technique have changed since this time.

The purpose of the study was to compare the lower extremity kinematics and knee joint kinetics displayed during stair ascent of MED- UKA and LAT-UKA individuals as compared to equivalent, healthy control individuals (MED-CON and LAT-CON, respectively). We anticipated that during the UKA limb stance phase of stair ascent, for equivalent limbs of their CON group, that the MED-UKA and LAT-UKA group operated limbs would exhibit: a) greater knee adduction/internal rotation and abduction/external rotation displacements, respectively; and b) greater and lesser peak knee adduction and internal rotation moments, respectively.

Methods

Participants

All participants provided written informed consent as approved by the Human Subjects Institutional Review Board of both institutions involved (see Appendix A). A total of 26 healthy UKA participants, 17 MED-UKA and 9 LAT-UKA, with a primary knee arthroplasty were recruited for the study. For UKA participants, 14 MED- and 6 LAT- UKA participants had a Cardo Align 360[®] Unicompartmental Knee System implant (Cardo Medical, Beverly Hill CA), and 3 MED- and 3 LAT- UKA participants had a Zimmer Unicompartmental High Flex Knee System[®] (Zimmer, Warsaw IN) implant. All participants had the UKA performed by the author (O. M. M.) at least 6 months prior to testing (ranged from 6 months to 3 years). Via answers to a health

questionnaire and medical clearance provided by the UKA surgeon, potential participants who had another implant in any lower limb joint, or had a medical condition or disease that potentially could have affected their performance or health were identified and excluded from this study. Twenty-six healthy CON participants were recruited who matched pair-wise with the individuals of the two UKA groups by gender (same gender), age (50 – 64 yr, ± 10 yr; 65 – 69 yr, ± 5 yr, and ± 3 year when age is over 70), height (± 5 cm), weight (± 7 kgs), and physical activity level (sedentary, moderately active or very active, based on American Heart Association Guidelines) as determined from the CHAMPS physical activity questionnaire [21]. Participant characteristics for each group and surgical-related information are shown in Table 4.1.

Experiment Protocol

All testing was performed in a biomechanics laboratory. Anthropometric characteristics were obtained. Next, to determine leg dominance, all performers kicked a ball several times. Thus, for CON individual, their limb of interest was the limb that had the same leg dominance as their matched counterpart's UKA limb. Following the suggestions of Cappozzo [22], 36 reflective markers (14 mm diameter), including 30 lower extremity markers [23, 24] and 6 upper-trunk and head markers were placed on the participant (see Appendix B). An additional six markers were placed on the steps to identify their spatial locations later. The participant completed a warm-up and practiced stair locomotion, then one trial of quiet natural standing was collected for later analyses.

For the task, the participant walked 2 steps on the ground, then continued to ascend 3 stairs (step height: 20 cm; depth: 28 cm) barefoot at a self-selected speed. Participants performed five successful trials starting with the right and five with the left limb. Limb order was

counterbalanced within each group. A successful trial was determined to occur if the performer ascended the stairs using a walking-style gait. Moreover, for the foot that contacted the force platform, the foot could not simultaneously be touching the platform and any other part of the stairs. Reflective marker locations of the performer were recorded by a seven-camera motion capture system (Vicon MX-40[®], Vicon, Los Angeles, CA; 120 fps). One force platform (AMTI[™] OR6-6-1[®], Advanced Mechanical Technology, Inc., Newton, MA), embedded in the floor in front of the steps, and a second platform (FP4060-NC[®], Bertec[®], Columbus, OH), embedded in the first step, were used to measure ground reaction forces (GRF) of each foot (1200 Hz).

Data Reduction

Raw marker locations were reconstructed into 3-D coordinates using Vicon software (Workstation[®] v5.2.4). All other data processing was performed via author-developed programs written in MATLAB[®] 7.0 (Mathworks, Inc. US). To define the movement intervals of interest, the stride of the limb of interest (UKA or matched CON limb) was initiated when the foot of the limb of interest contacted the first step and ended when the same foot contacted the third step. The foot strike and off on the first step were determined by vertical ground reaction force (GRF) signal, and the foot strike and off on the third step were determined when the toe marker passed the lined of 3rd step markers.

For kinematic data, raw coordinate data were smoothed using generalized cross-validatory spline (GCVSPL) smoothing techniques [25]. The pelvis, thigh, shank and foot were modeled as rigid segments connected by frictionless joints using Lu's method [24, 26]. A local coordinate system (LCS) of each segment was defined from marker locations displayed during the natural standing trial (see Appendix C). The LCS, joint type, center of rotation, and rotation axes of the

lower extremity joints were defined following recommendations of Cappozzo [22] and International Society of Biomechanics [27, 28]. The LCSs were used to generate the rotation matrices of the distal body segment relative to the proximal segment. In stair ascent trials, an unweighted least-squares method was applied to smoothed marker locations to reduce skin movement artefacts and to reconstruct dropped marker trajectories [29]. Joint angles of the lower extremities of the limb of interest were defined using Cardan angles (rotation sequence = z-y-x, which was flexion(+)/extension, internal(+)/external rotation, and adduction(+)/abduction, respectively) [30]. The lower extremity joint angles exhibited during stair ascent were adjusted to the joint angles displayed during natural standing.

For kinetics calculations, inverse dynamics were used to generate joint moments and powers of the joints of the limb of interest [31] for the support phase when the limb was on the stair force platform. A fourth-order, low-pass Butterworth filter (cutoff frequency = 100 Hz) was applied to the ground reaction force and moment signals. Masses, center of mass locations, and moments of inertia of the segments were estimated using anthropometric coefficients of Dempster's as summarized in Winter [31]. Joint moment and power magnitudes were scaled by body mass and leg length. Details of the mathematics are summarized in Appendix C. Knee joint powers were calculated to help explain the behavioral purposes of the corresponding joint moments. GRF from the floor platform were used only to identify events within the stride of interest.

Data Analysis

Step and stride characteristic variables were generated. Angular displacements for all lower extremity joints, and peak knee joint moment magnitudes and times to peak moments for the

stance phase of the limb of interest for each group were the variables of interest. Only peak knee joint moment events common to all individuals were identified for statistical analysis.

For participant characteristics, paired t-tests were used to compare between UKA and CON groups, and independent t-tests were used to compare between CON groups. For all variables, paired t-tests were used to compare each UKA group to the corresponding matched CON group (SPSS v.18.0, SPSS Inc., Chicago, USA). All tests were considered statistically significant at $p < 0.05$. Statistical power and effect size (Cohen's d) were generated (G power 3) [32]. A statistically significant variable displaying a moderate (0.3 to 0.5) or higher effect size was considered to have behavioral meaning.

Results

The results of statistical comparisons between each UKA group and its corresponding CON group for relevant participant characteristics (Table 4.1) showed that the UKA limb leg length of MED-UKA was 4 cm shorter than the matched limb of MED-CON ($d = 0.789$). There were no other group differences for these variables.

Six spatio-temporal stride variables were significant between a UKA and its CON group (Table 4.2). Both CON groups had approximately 0.2 s shorter stride time than their corresponding UKA groups (MED-UKA, $d = 0.677$; LAT-UKA, $d = 0.969$). Both UKA groups had lower walking speed than their corresponding CON groups (MED-UKA, $d = 0.689$; LAT-UKA, $d = 1.165$). The MED-UKA group had approximately 3% longer stance phase than the MED-CON group ($d = 0.744$).

For angular kinematics, the MED-UKA group had approximately 5° less maximum knee extension displacement than the MED-CON group during the stance phase ($d = 0.616$, Table 4.3).

The knee flexion angle at initial foot contact on the 1st step was then tested using pair t-test between MED-UKA and MED-CON. The knee flexion angle at initial foot contact on the 1st step of MED-UKA ($58.8 \pm 6.7^\circ$) demonstrated approximately 8° less than that of MED-CON ($66.3 \pm 7.2^\circ$, $p < 0.000$, $d = 1.067$). The LAT-UKA group had 5° greater maximum hip abduction displacement than LAT-CON ($d = 0.886$). The other kinematic variables were not significant.

For knee kinetic variables, no significant differences were found for any peak joint moment or power magnitudes or time to peak moment values (Table 4.4). For joint powers of all three axes, only the knee flexion/extension axis powers displayed any consistent pattern among participants, and thus, were the only joint powers presented.

Qualitatively, two knee joint moment-time patterns were detected for each axis of rotation. The ensemble moment patterns (and joint angles) of representative participants displaying each these categories (and the moment peaks tested statistically) are shown in Figure 4.1. Figure 4.2 shows the participant frequency distributions of the moment pattern categories for all groups. There did not appear to be sizeable differences between UKA groups and their CON groups for the percentage of participants who exhibited particular patterns for any planes. Additionally, from visual inspection of individual participant graphs, a particular pattern of one plane did not appear to be consistently associated with a particular pattern of the other planes.

For both knee joint moment patterns of the sagittal plane, the knee moment displayed an eccentric flexion moment during the initial stance phase, then concentric extension moments until 50% of the stance phase. Next, the patterns diverged until approximately the last 90% of the stance phase: Pattern 1 displayed a concentric flexion moment, whereas, for Pattern 2, a burst of concentric extension moment was produced. Both patterns were eccentric knee flexion during the remainder of the stance phase. For the knee joint moment patterns of the frontal plane,

Pattern 1 displayed abduction moments during the entire stance phase, while Pattern 2 was adduction during the first half, then, like Pattern 1, was abduction until the end of the stance phase. For moment patterns of the transverse plane, during approximately the first half of the stance phase, Pattern 1 and Pattern 2 displayed internal and external rotation moments, respectively; then both patterns consisted of external rotation moments acting up to the late stance phase.

Discussion

In the current study, we sought to determine if three-dimensional knee biomechanics of stair ascent of UKA were typical or atypical compared to healthy control individuals. It was predicted that the operated limbs of MED-UKA and LAT-UKA groups would exhibit greater knee adduction/internal rotation and abduction/external rotation displacements, respectively during stance phase of stair ascent. It was also predicted that MED- and LAT-UKA groups displayed greater and lesser maximum knee adduction and internal rotation moments, respectively. Results of current study showed that generally both UKA groups demonstrated typical knee biomechanics of stair ascent, with only two spatio-temporal kinematics and two joint kinematics variables demonstrate significant differences to support predictions. No differences were found in joint kinetics variables, and two knee moment patterns were found. One of the patterns might be prone to increase axial and shear loading on the implant side of MED-UKA and the healthy condyle of LAT-UKA individuals, respectively.

Both UKA groups showed 0.2 s longer stride time and slower walking velocities compared to CON groups (Table 4.2). Compared to other stair ascent literature, both MED- and LAT- UKA groups also ascended more slowly than healthy individuals [33, 34], but within 2% of TKA

individuals' [35]. This finding indicates that, when using walking speed to evaluate functional performance after surgery, the UKA individuals' speeds of both UKA groups are closest to speeds of TKA individuals, and still slower than healthy individuals.

The slower ascent speed of UKA versus CON groups may be related to the longer stance phase time. Results showed that MED-UKA individuals displayed approximately 3% longer stance phase time than MED-CON individuals. Although current study didn't found difference between LAT-UKA and –CON groups, LAT-UKA individuals displayed approximately 2% longer stance phase time compared to healthy individuals in other stair ascent literature [34]. It implies that both UKA groups have tendency to slow down walking velocity during the stance phase, perhaps to increase knee joint stability.

Results of joint kinematics also did not support predictions in current study, as few statistically significant outcomes occurred. Low statistical power likely affected these tests, but there also is the possibility that UKA individuals might demonstrate typical joint kinematics during stair ascent (Table 4.3). Qualitatively, lower extremity kinematic patterns of both UKA and CON groups during stair ascent were consistent with those demonstrated in prior literature [34, 36-38]. Angular displacements of the lower extremity of UKA groups had no difference to their CON group except for two variables, and were consistent with values demonstrated in prior literature of healthy young and older individuals [33, 34, 37].

For kinematics that were different between UKA and the corresponding CON group, with MED-UKA having 5° less knee joint extension displacement than MED-CON, and LAT-UKA having 5° greater hip joint abduction displacement than LAT-CON during stance phase. The decreased MED-UKA knee joint displacement might be due to the leg length difference rather than UKA implant type. Results of knee flexion angle at initial foot contact on the 1st step of

MED-UKA was approximately 8° less than that of MED-CON. Thus, with a 4 cm longer leg length than the MED-UKA group, the MED-CON group initiated foot contact at a higher knee flexion angle than MED-UKA, thus MED-CON extended the knee joint through a larger displacement to reach full extension during the stance phase.

For joint kinetics, no significant differences for peak magnitudes or times to peak magnitudes may be due, in part to a lack of statistical power. There was a trend ($p = 0.08$), however, for the LAT-UKA group to display a lower peak flexion moment compared to the LAT-CON group (Table 4.4). This would be expected, as the LAT-CON group's stair ascent speed was greater, and knee joint moments in the frontal plane help generate/control speed. Maximum knee extension moments in this current study were within the range of values reported for young and healthy older adults [33, 34, 38]. MED-UKA showed larger and MED-CON showed slightly larger peak abduction moments, and similar peak external rotation moments than values published studies [33, 36]. Peak moment values likely vary among studies due to different stair dimensions used, and perhaps, participant characteristics, such as age, physical activity level and lower extremity muscle strength. For all participants in our study, their ages were from 50 to 78 yrs and physically active. Although peak moments of UKA groups in the current study do not differ from CON groups, it might potentially have higher peak moments if they walked at the same speed as CON individuals.

Qualitatively, as the two knee joint moment patterns for each axis of rotation were displayed by nearly the same number of individuals in the CON groups compared to their UKA groups, it is surmised that the particular knee moment patterns used were unrelated to the UKA. These patterns have been observed to occur by other researchers in young and older adults [33, 34, 36-40], except for Pattern 2 in the transverse plane. The patterns displayed by older adults (the

Pattern 2's in Figure 4.1 middle row) have been surmised to occur as an adaptation for decreased leg muscle strength and different strategies to accomplish stair ascent [38]. However, there is no sufficient evidence to confirm the second reason in current study.

Participant frequencies of the knee moment patterns also supported that UKA groups displayed typical moment patterns as CON groups did (Figure 4.2.). About two-third of all participants showed Pattern 1 and the rest showed Pattern 2 on all three axes. It is interesting that MED-UKA had higher frequency in Pattern 1 (displayed by younger population in the literature) than CON and LAT-UKA groups. Unfortunately, there is no clear answer for it, and age and physical activity capacity might be confounding factors. In addition, the knee does not exhibit pure pattern I (extension-flexion/abduction-adduction/internal rotation-external rotation) or pattern II (extension- extension / adduction - abduction / external rotation - external rotation), and those different patterns did not consistently occur in only MED- or LAT- UKA (Figure 4.2). Yet reason for this phenomenon is not clear in the study.

However, for those UKA individuals who displayed adduction and external rotation moments rather than abduction and internal rotation knee moments during the latter half of the stance phase, it is possible that they may be prone to increased axial and shear loading on the implant side of a MED-UKA knee and the healthy condyle of a LAT-UKA knee, which might lead to increased wear on the articulating surfaces [41]. Unfortunately, this cannot be proven with these data.

Several potential limitations existed. One major limitation of the study was small sample size, especially for the LAT-UKA group. A *post-hoc* power analysis showed that current study should recruit more participants to detect difference for kinetic variables. Sample size for spatio-temporal variables is sufficient, and at least 10 more participants (up to 34) for each LAT

group are required to detect kinematic variable differences. For kinetics variables, it requires at least 17 more participants for MED groups and 1 more participant for LAT groups. Considering the feasibility of recruitment, 20 participants per group would be a feasible size. Both MED and LAT groups in current study are lower than 20 indicated that there is some chance for Type II error, and especially higher in LAT groups. Individual differences within a group also affected statistical power and effect size. For example, the coefficient of variation for joint moment variables ranged from 0.16 (1st peak extension moment) to 0.7 (2nd peak external moment). Another potential limitation was skin movement artefact, However, in addition to smoothing the raw coordinate data, the unweighted least-squares method for the equiform transformation that was applied to the coordinate data has been shown to reduce artefact effects [29].

In conclusion, it is likely that MED- and perhaps LAT-UKA individuals may have demonstrated typical knee biomechanics for stair ascent. Based on these data, both MED- and LAT- UKA are potentially a considerable choices for severe OA treatment. Recruiting more participants in the future would help to strengthen findings in current study.

Conflict of interest

There is no conflict of interest.

Acknowledgements

The authors thank Megan Johnson for her assistance with recruiting participants. The authors thank Athens Orthopedic Clinic and St. Mary's hospital staffs for their assistance with data collection.

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Tables

Table 4.1 Participant characteristics (mean $\pm$ SD) for medial (MED) and lateral (LAT) unicompartmental knee arthroplasty (UKA) participants and their matched control groups (MED-CON and LAT-CON).

	Gender (n)	Ages (yrs)	Height (cm)	Mass (kg)	UKA/matched limb Leg length (cm)
MED-UKA	M: 6; F: 11	68.0 $\pm$ 7.4	162.7 $\pm$ 7.1	74.1 $\pm$ 12.3	85.3 $\pm$ 4.2 [†]
MED-CON	M: 6; F: 11	67.4 $\pm$ 8.9	165.4 $\pm$ 9.3	70.3 $\pm$ 14.0	89.3 $\pm$ 6.6 [†]
LAT-UKA	M: 3; F: 6	63.1 $\pm$ 7.8	167.2 $\pm$ 6.4	71.1 $\pm$ 13.3	89.9 $\pm$ 3.5
LAT-CON	M: 3; F: 6	63.1 $\pm$ 7.0	168.7 $\pm$ 8.0	70.0 $\pm$ 14.3	89.8 $\pm$ 4.4

[†] A significant difference was found between MED-UKA and MED-CON ($p < 0.05$, effect size = 0.789).

Table 4.2 Spatio-temporal variables (mean $\pm$ SD) of medial (MED) and lateral (LAT) unicompartmental knee arthroplasty (UKA) participants and their matched control groups (MED-CON and LAT-CON). Bolded numbers indicate the UKA group is significantly different from corresponding CON group ($p < 0.05$).

	Stride Time	Relative Time (% Stride)		Stride Length	Stride velocity
	(s)	Stance Phase	Swing Phase	(cm)	(cm/s)
MED-UKA	1.51 $\pm$ 0.24	67.1 $\pm$ 2.6	32.9 $\pm$ 2.6	56.2 $\pm$ 2.5	38.3 $\pm$ 7.3
MED-CON	1.35 $\pm$ 0.16	64.4 $\pm$ 2.1	35.6 $\pm$ 2.1	57.6 $\pm$ 1.9	43.5 $\pm$ 5.6
<i>p</i> value	0.013	0.007	0.007	0.156	0.012
Cohen's d	0.677	0.744	0.744	0.361	0.689
LAT-UKA	1.61 $\pm$ 0.21	64.3 $\pm$ 2.8	35.7 $\pm$ 2.8	57.9 $\pm$ 1.2	36.5 $\pm$ 4.8
LAT-CON	1.38 $\pm$ 0.20	65.2 $\pm$ 1.0	34.7 $\pm$ 1.0	58.7 $\pm$ 2.2	43.2 $\pm$ 5.3
<i>p</i> value	0.018	0.394	0.233	0.736	0.009
Cohen's d	0.990	0.300	0.300	0.430	1.165

Table 4.3 Joint displacement variables (°) of medial (MED) and lateral (LAT) unicompartmental knee arthroplasty (UKA) participants and their matched control groups (MED-CON and LAT-CON).

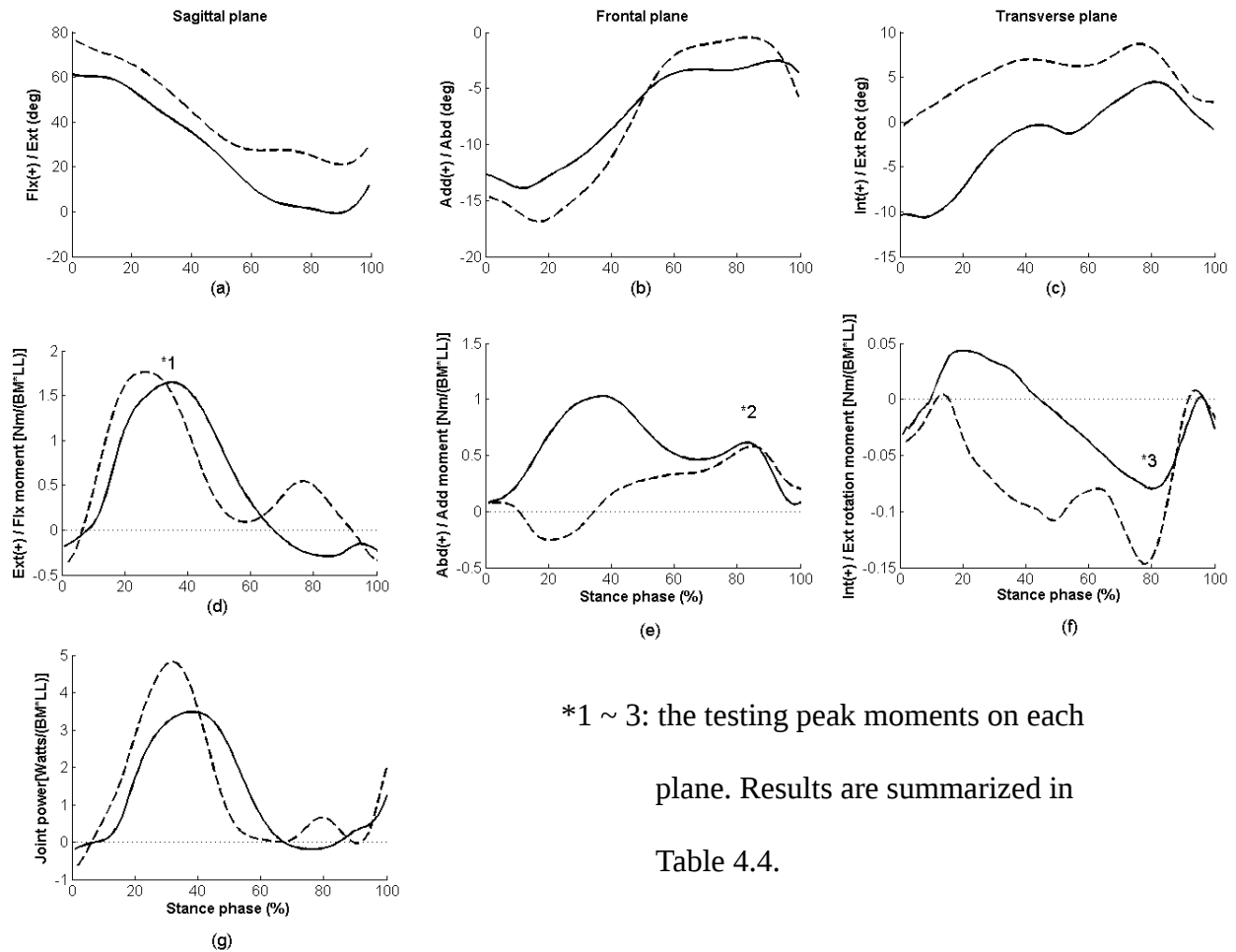
	Hip		Knee			Ankle		
	Ext	Abd	Ext	Add	Int Rot	Dorsi- flex	Planta- Flex	Abd
MED-UKA	54.3±4.9	14.1±6.2	52.7±5.1	11.0±5.1	14.7±4.9	8.4±3.6	41.4±6.4	5.8±2.2
MED-CON	52.4±4.3	12.1±3.5	57.2±5.5	9.9±4.9	15.0±4.6	6.9±4.0	39.2±5.7	5.4±1.9
<i>p</i> value	0.191	0.306	0.022	0.579	0.856	0.208	0.167	0.640
Cohen's d	0.331	0.256	0.616	0.138	0.045	0.318	0.351	0.116
LAT-UKA	53.1±6.0	16.9±6.8	58.4±6.1	8.8±6.9	14.1±7.4	8.3±3.8	37.7±6.6	5.7±1.6
LAT-CON	52.4±6.4	12.0±3.2	54.9±5.1	12.3±6.0	15.8±4.8	7.4±3.8	37.6±5.1	5.1±1.2
<i>p</i> value	0.711	0.041	0.190	0.218	0.385	0.670	0.467	0.497
Cohen's d	0.136	0.886	0.478	0.445	0.306	0.147	0.010	0.406

Note: Ext/Flex = extension/flexion; Abd/abd = abduction/adduction; Int Rot = internal rotation.

Table 4.4 Peak knee joint moment magnitudes (Nm/body mass/leg length) and time to peak moments (% of stance phase) of medial (MED) and lateral (LAT) unicompartmental knee arthroplasty (UKA) participants and their matched control groups (MED-CON and LAT-CON). See Figure 4.1 for descriptions of these variables.

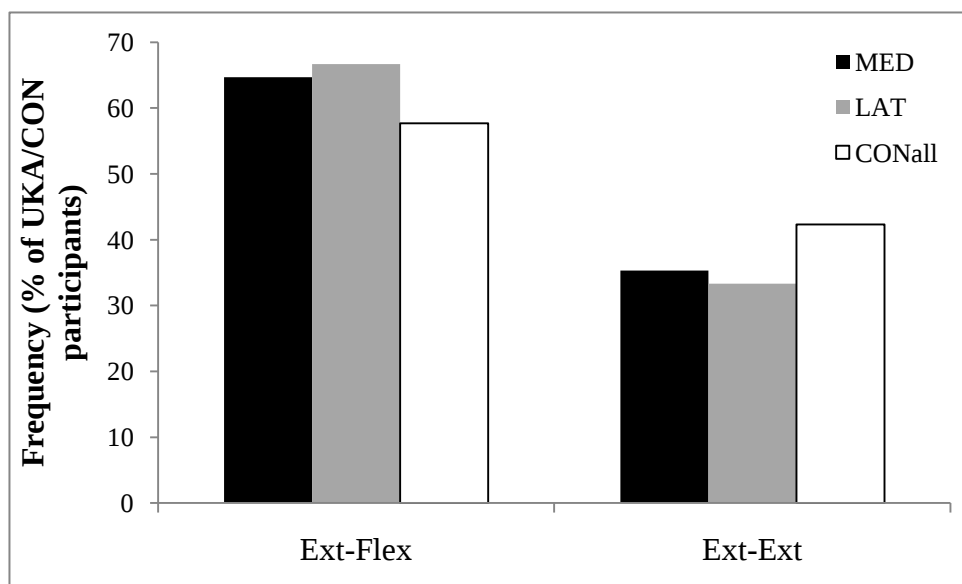
	1 st peak Extension moment		2 nd peak abduction moment		2 nd peak external rotation moment	
	Peak value	Time to peak	Peak value	Time to peak	Peak value	Time to peak
MED-UKA	1.21 ± 0.19	30.2 ± 2.2	0.63 ± 0.28	71.8 ± 10.9	0.10 ± 0.07	78.9 ± 10.6
MED-CON	1.31 ± 0.30	29.7 ± 3.5	0.51 ± 0.30	71.1 ± 12.7	0.07 ± 0.07	80.9 ± 7.8
<i>p</i> value	0.305	0.305	0.171	0.862	0.225	0.526
Cohen's d	0.257	0.154	0.347	0.043	0.307	0.157
LAT-UKA	1.02 ± 0.17	30.4 ± 3.6	0.40 ± 0.19	68.2 ± 10.3	0.07 ± 0.04	81.4 ± 4.1
LAT-CON	1.29 ± 0.31	30.5 ± 3.2	0.40 ± 0.20	73.4 ± 10.3	0.08 ± 0.04	80.4 ± 7.0
<i>p</i> value	0.082	0.932	0.976	0.386	0.822	0.710
Cohen's d	0.661	0.029	0.010	0.306	0.079	0.128

Figures

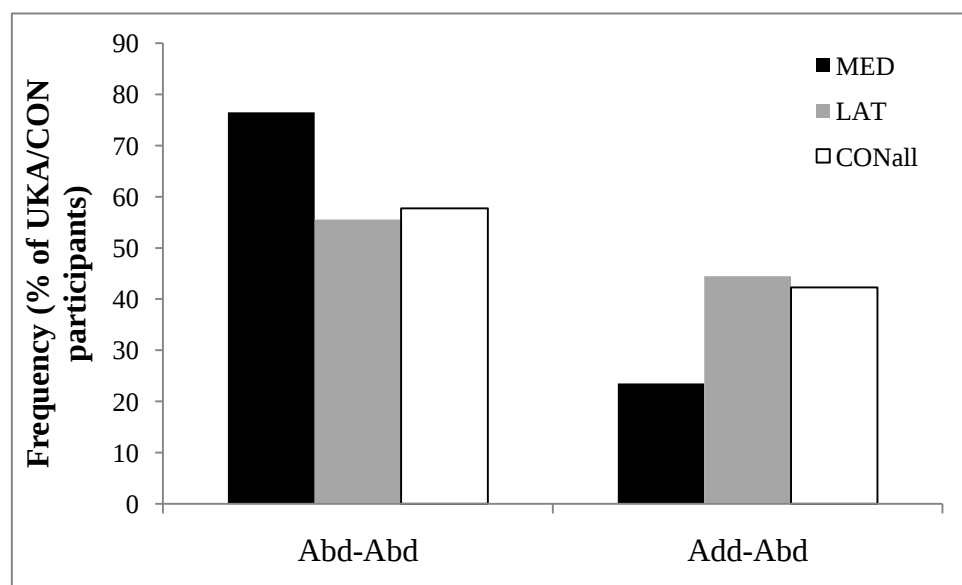


*1 ~ 3: the testing peak moments on each plane. Results are summarized in Table 4.4.

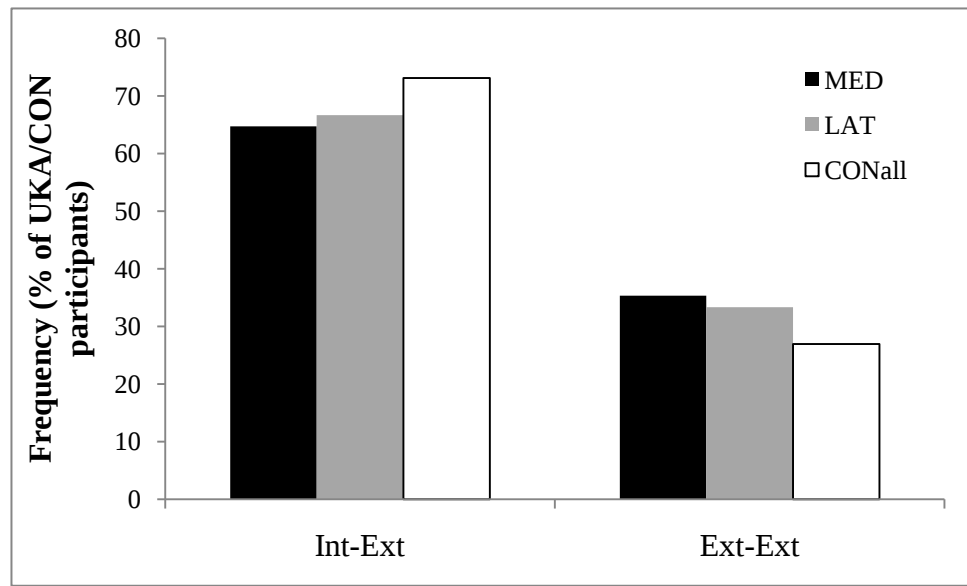
Figure 4.1 Ensemble knee joint angles (top row), joint moments (middle row) and joint powers (bottom row) of representative three participants. No common joint power patterns were displayed among participants for the frontal and transverse planes, thus, they are not shown. For each plane, among participants of all groups, two distinct moment-time patterns were exhibited (dashed and solid lines). Patterns exhibited in one plane were not necessarily associated with a particular pattern in either of the other planes.



(a)



(b)



(c)

Figure 4.2 Participant frequencies of the UKA and CON groups (%) of Pattern 1 and Pattern 2 of knee moments on a) sagittal, b) frontal, and c) transverse plane.

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

Due to the renewed interest in using UKA as an appropriate treatment for certain knee OA patients (Saito, Takeuchi, Yamamoto, Yoshida, & Koshino, 2003), the importance of understanding the biomechanics of UKA individuals during functional, weight-bearing activities also has increased. Although current UKA have better clinical outcomes than those performed in the 1950s (Tanavalee & Yuktanandana, 2003), knowledge of biomechanics of individuals who have had a more recent UKA is still limited. Furthermore, understanding of LAT-UKA biomechanics is particularly lacking. Therefore, the purposes of the current two studies were to: for Study #1, describe and compare the *in-vivo* kinematics of the tibio-femoral joints of MED-UKA and LAT-UKA individuals for a step-up task; and for Study #2, to investigate if the biomechanics of MED-UKA and LAT-UKA individuals were similar to the biomechanics displayed by healthy individuals during stair ascent.

Fourteen MED-UKA and eight LAT-UKA participants ($n = 14$ and 8 , respectively), with preoperative deformities ranging from 10° valgus to 7° varus were recruited for the first study. For the second study, two UKA groups MED-UKA and LAT-UKA ($n = 17$ and 9 , respectively) and two groups of matched-pair control participants corresponded to each UKA group were formed.

For Study #1, UKA participants received a CT scan of the operated knee joint region to be used with a CAD model of the implant components to generate a hybrid bone-implant model of the proximal tibia and distal femur for later use during fluoroscopy image registration. A sagittal plane view of the knee region was captured by a videofluoroscopy system when the participant

performed the stance phase of a step-up motion with the UKA limb. Tibio-femoral angular displacements and A-P translations of each tibio-femoral compartment were compared between the UKA limbs of the two groups using one-way ANOVA ($p < 0.05$).

Tibio-femoral angular and posterior linear displacements of study #1 were not different between groups. Descriptively, MED-UKA and LAT-UKA groups, respectively, demonstrated angular displacements of $11.4 \pm 6.6^\circ$ and $6.5 \pm 3.6^\circ$ internal rotation and $6.1 \pm 2.3^\circ$ and $4.7 \pm 1.6^\circ$ for abduction displacements. For posterior translation, MED-UKA and LAT-UKA, respectively, exhibited 10.64 ± 8.83 mm and 13.8 ± 6.0 mm on the medial condyle of the femur and 13.2 ± 6.9 mm and 9.7 ± 7.7 mm on the lateral condyle of the femur.

For Study #2, all participants performed stair ascent while spatial locations of reflective markers using high-speed digital video and ground reaction forces signals from force platforms were captured. Stance and stride phase characteristics and angular kinematics and kinetics of the lower extremity of the UKA limb of each UKA group and the corresponding limb of the CON groups were compared using paired t-tests. The frequency of participants within each group that displayed each particular knee joint moment pattern was described.

Results of study #2 showed that participant characteristics were not significantly different between UKA and CON groups, except that the MED-UKA group had a 4 cm shorter leg length than MED-CON group. Among spatio-temporal gait variables, both UKA groups demonstrated longer stride times and slower walking velocities compared to CON groups. For the stance phase, the MED-UKA group had approximately 5° less knee extension displacement, and the LAT-UKA group had 5° greater hip abduction displacement than the corresponding CON group. No other statistical significance was found for other kinematic or kinetic variables. However, two different knee joint moment patterns for all planes were displayed among the participants. The frequency

of participants within each group exhibiting a particular pattern was similar among groups.

In general, the predictions that LAT-UKA would display different tibio-femoral kinematics than MED-UKA during step rising and ascent, and both UKA groups would display differences for kinematics and kinetics compared to their control groups for stair ascent were not supported. This was likely due partly to lack of statistical findings affected by low statistical power for some variables. However, both MED- and LAT-UKA individuals displayed knee kinematics that were mostly typical when compared to values of healthy knees from the literature (Study 1) and their respective control groups' values (Study 2).

Results of study#1 also showed findings that were opposite to those anticipated for each UKA group for posterior translation. It had been predicted that, MED-UKA compared to LAT-UKA, would have greater tibio-femoral posterior translation at the medial condyle of the femur, and lesser translation at the lateral condyle of the femur. The nonoperated condyle in both UKA groups was expected to exhibit posterior translation similar to that of typical, nonoperated limbs in the literature. Although no significances were found between UKA groups, the posterior translations of the lateral and medial condyles of the MED-UKA compared to LAT-UKA tended to exhibit greater and lesser translation, respectively. Several potential explanations exist for the translation findings, such as the effects of scarring, pre- and/or post-op varus/valgus alignment, type of implant components (Saito et al., 2003), etc. that are not provable at this time.

For study #2, the two significant angular kinematics outcomes between a UKA group and corresponding CON group were not expected. The reduced knee extension displacement of the MED-UKA compared to the MED-CON group was likely to be affected, in part, by leg length rather than implant type. The reasons for the LAT-UKA group's approximately 5° greater hip abduction displacement compared to the displacement of the LAT-CON's are unclear, perhaps

compensation mechanism happens in the pelvis during ascent.

Also in study #2, knee moments were not significantly different between UKA and corresponding CON groups, and did not support predictions. Qualitatively, the different knee joint moment patterns found for each axis direction did not seem to be affected by UKA implant type. This was because the percentage of participants who displayed these patterns was roughly similar among groups. Participants who demonstrated knee adduction moments during the first half of the stance phase displayed a pattern similar to those of older adults in the literature (Novak & Brouwer, 2010). Adduction and external rotation moments during early stance phase may cause more axial and shear loading on the implant side of MED-UKA and the healthy condyle of LAT-UKA individuals, which could lead to progress wearing or increased joint degeneration, respectively.

Conclusions

Based on findings of both studies, I believe that both MED- and LAT-UKA are good treatments for OA, because results of both studies showed similar kinematics and kinetics patterns compared to healthy individuals and did not support predictions, which indicated both UKA groups demonstrated typical knee biomechanics. Furthermore, I believe that MED-UKA individuals show some slightly better biomechanical outcomes than LAT-UKA individuals. Reasons for that are: 1) MED-UKA knees demonstrated closer kinematics than LAT-UKA compared to healthy knees published in the literature in study #1, and 2) in study #2 more LAT-UKA individuals demonstrated knee ad/abduction moment pattern that may potentially do harm to the UKA knee joint surface.

Recommendations

The findings of these studies should be confirmed with greater numbers of participants, especially LAT-UKA individuals. In addition, large samples of normative data of the biomechanics displayed by healthy individuals for stair ascent are needed for comparison to the biomechanics displayed by clinical. Furthermore, obtaining EMG of major lower extremity muscles would help to distinguish motor control strategies used among typical and UKA individuals. At last, biomechanical modeling would help to determine if different moment patterns potentially cause abnormal wearing of UKA knees.

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APPENDIX A:

FORMS AND QUESTIONNAIRES

Item 1.1 (FOR UKA participant)

INFORMED CONSENT FOR RESEARCH PARTICIPATION

I, _____ agree to participate in the research study entitled, “*Effects of varus/valgus preoperative deformity on the biomechanics of unicompartmental knee arthroplasty individuals*”, that is being conducted by Dr. Kathy Simpson (706-542-4385) and Mr. Yang-Chieh Fu (graduate student, 706-542-4132), Department of Kinesiology at the University of Georgia, Athens, GA, and Dr. Ormonde Mahoney (706-549-1663) and Ms Tracy Kinsey (706-549-1663), Athens Orthopedic Clinic, PA. I understand that this participation is entirely voluntary; I can refuse to participate or withdraw my consent at anytime without penalty or loss of benefits to which I am otherwise entitled. I can have the results of my participation, to the extent that can be identified as mine returned to me, removed from the research records, or destroyed. Additionally, if I am ineligible or become ineligible during my participation in the study and am released from further involvement in the study by the researchers, there also are no penalties or financial charges. My decision to participate/not participate or to withdraw my consent at any time if I so choose, will in no way affect any current or future medical treatments that I receive or will receive from Athens Orthopedic Clinic.

The purpose of the study is to investigate the biomechanical factors related to physical function after having had a unicompartmental knee arthroplasty (UKA). We believe that the information gained from this study will help us understand how well the knee functions and how it moves after having this type of knee replacement surgery. We are particularly interested in investigating how the UKA knee performs during high demand daily activities in comparison to knees have not undergone a partial knee replacement, as this is not currently known.

I may benefit by developing a greater understanding of the general benefits of unicompartmental knee arthroplasty, and, if I so desire, my data will be shown to me, and an informal assessment of my performances will be given to me at the end of my testing. If I so request, I can be provided with a more substantial analysis that may be useful to share with my surgeon or physician.

To be eligible, I must be healthy, free from any leg, foot, back or neck pain, or injury having required major medical attention or surgery; and free from any medical condition that is a) not under control or b) not monitored/treated by a medical physician or c) may adversely affect my safety or performance

If I am female, I cannot be pregnant. If pregnant, the radiation procedures may involve risks to the embryo or fetus, which are currently unforeseeable. Thus, if I am female and unsure whether I am pregnant, I will be given a home pregnancy test kit at no cost to me; and I will take the test at a location/time of my choice. It is my responsibility to determine my pregnancy status and the results of pregnancy test must be negative to be eligible to participate. If I choose to take the pregnancy test, I am not required to divulge any personal information about my pregnancy status or the outcomes of the pregnancy test.

My part in this study will last for approximately 3.5 hours of physical testing and approximately ½ hr to complete the two questionnaires that are to be completed prior to the testing session. The procedures are

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as follows: I will come to the Athens Orthopedic Clinic, and I will sign this informed consent form after having the procedures explained to me and any questions I have answered. Next, we will determine my eligibility to participate in the study. First, the researcher will review with me my answers on the confidential, current health status questionnaire that I completed before the test session began. This questionnaire contains my history of injury/disease and any known balance difficulties. The second questionnaire I will complete prior to testing is for informational purposes only to help us understand the physical activities I typically engage in. The researcher will also inquire if I have any new injuries, illnesses or symptoms of pain or discomfort. Next, if Dr. Mahoney was my knee surgeon, he will provide medical clearance for me to participate in this study if he believes that my health status meets the criteria for me to participate, and I do not have any disallowed health conditions. Otherwise, if he was not my knee surgeon and/or I would prefer to have another physician provide my medical clearance, the researcher will ask for my signed medical clearance form before proceeding.

I will then have the lengths and alignments of both legs measured and visually assessed, respectively. At this time, I will be told whether I will continue with the testing or be released from further participation. If I am ineligible, all forms I completed and my data can be returned to me or I can have the researchers put them into a sealed envelope, and then destroyed immediately.

Note. The researchers also reserve the right, now or at any time during testing, to ask for additional medical clearance from my physician before further testing can occur if they believe that I may have a health condition/injury/impairment that could affect my ability to safely complete the tasks, or if I am unsure that any medical conditions, impairments or illnesses I have may affect my safety or performance.

If I am eligible to continue participation, if feasible, all study procedures will be accomplished in one day. However, it also is possible or may be necessary to complete the tasks over multiple days.

I will then fill out a physical activity questionnaire. Next, for the first physical task, I will perform 3 repetitions of stepping up and back down from a small step while my operated limb is videotaped using a videofluoroscope machine. Then I will perform 3 repetitions of squatting down and standing back up. During tasks, I will wear a lead vest to protect my trunk and pelvis from radiation exposure. Fluoroscopy is similar to x-ray techniques (radiography) but at a lower radiation-dosage. Researchers have estimated that the maximum, possible radiation dosage (which is unlikely to occur) I might receive will be no more than 1.2 mSv, approximately 1/7th of a typical abdominal CT scan (8 mSv).

Accompanied by a researcher, I then will go to St. Mary's to have a CT scan of my operated knee starting at about 6 inches (15 cm) below to 6 inches (15 cm) above the center of my knee joint. The actual scan will take approximately 15 minutes. The radiation dosage for the CT scan will be 0.5 to 0.8 mSv. The approximate maximum radiation I might receive would be 2 mSv (the annual radiation exposure limit for the whole body is 5,000 mSv).

Last, I will go to the UGA Dept. of Kinesiology's Biomechanics Laboratory (Rm 103, Ramsey Center, Academic Wing). A researcher can accompany me from St. Mary's to UGA if I desire. Certain measurements of my body dimensions, e.g., height, weight, will be made. Similar to how animations are

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made for movies and video games, I will have reflective markers placed on various locations on my skin and/or clothing. The locations of these markers will be captured during testing by special, digital motion cameras. These marker locations are used later to reconstruct the movements of my body and limbs. I will undergo a warm-up consisting of 2-3 minutes of warm-up consisting of walking up and down the stairs at a natural pace with brief pauses at the top and the bottom of the stairs. I then will practice walking up and down a short set of steps. Next, I will perform the task of walking up the steps and stopping; then walking back down the stairs approximately 10 to 15 times. During each performance, I also will be stepping onto force plates (devices that measure forces that are applied to my feet from the ground during movement) that are embedded in the stairs and floor. I will be given at least 30 seconds to 1 minute of rest at the top of the stairs, and 1 minute of rest before I go back up the steps. I also can ask for longer rest periods at any time. One regular video camera will be used to capture my movements to help the researchers later track the marker movements only if necessary. This part of the testing will take approximately 2 hours. The markers will be removed, and if I wish, I can see an initial look at my movements, digital video files and/or some of my data.

Performing any physical activity has some inherent risk of injury. However, the potential risk of injury is minimal, as the two tasks involved are the same as these performed multiple times on a daily basis. Thus, the risk is much lower than the risk encountered by people while moving about during their everyday lives. Although I am healthy with good physical functional capacity, and therefore are very unlikely to trip, the following procedures or items will be put in place: a) a handrail is available for my use if needed; b) to avoid fatigue, I am required to only walk up 4 steps before resting, and given more rest after I walk down the 4 steps before starting up the steps again and can have as much rest as I wish; c) I will have a researcher close enough to me to catch me if I trip accidentally or appear to be losing balance, and d) I will have a designated researcher take care of me throughout the testing, including monitoring how I feel and watching me for any signs of discomfort or other problems; e) I will tell the researchers immediately if I feel any signs of discomfort, pain, dizziness or other physical symptoms that could influence my health and safety; and f) the researchers will stop testing immediately if any researcher believes that I not be able to perform the tasks safely or that I may be exhibiting symptoms of a physical problem.

Thus, I am informed that I am to tell the researchers immediately if I begin to experience any discomfort, pain, nausea, dizziness or other atypical physical symptoms. Testing will be stopped immediately, and the researchers and I will discuss whether the problem can be resolved immediately and testing can continue, or if I should postpone testing until a later date or the rest of the testing will be completely discontinued. Although unlikely, discomfort or muscle soreness in the legs may occur for a few days after participation, as can occur due to participating in any new physical activity. The researchers will exercise all reasonable care to protect me from harm as a result of my participation. In the event of an injury as an immediate and direct result of my participation, the researchers' sole responsibility is to transport me to an appropriate facility if additional care is needed. The researchers will not provide any compensation or payment for medical care. As a participant, I do not give up or waive any of my legal rights.

The only people who will know that I am a research participant are members of the research team and the doctor I choose to provide my physician clearance to participate. No identifying information about

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me or provided by me during the research will be shared with others, except if necessary to protect my rights or welfare (for example, if I am injured and need emergency care); or if required by law. Only research team members who assist with data collection will see me. All of my data will be coded using a participant ID number that is known only to the researchers. As only the reflective markers are visible to the special motion capture cameras, my recorded performances will be confidential and identifiable only by my participant number. The digital video files of my performances of the functional tasks will only be used by the researchers to help them track the marker locations from the other cameras if needed (which is rarely the case). All the rest of the data are non-identifiable. All data, including the electronic video files, will remain in a secured area. Personal health information will not be disclosed and used for any analysis. Only the primary and co-investigators will have access to the master list that identifies me with my participant ID number, as it will be kept secure and separate from other data files. The master list and digital video files will be destroyed when analysis is finished or 10 years from the start date of this study, whichever comes first.

For any further questions about the research please contact: Co-Investigator, Yang-Chieh Fu at 706/542-4132 (ycfu@uga.edu) or Principal-Investigator, Dr. Kathy Simpson, at 706/542-4385 (kjsimpsonuga@gmail.com).

I understand that, by my signature on this form, I am agreeing to take part in this research project and understand that I will receive a signed copy of this consent form for my records.

My signature _____ **Date** _____

Please sign both copies, keep one and return one to the researcher.

Name of Researcher(s)	Researcher Signature	Date
Dr. Kathy J. Simpson	706/542-4385 kjsimpsonuga@gmail.com	
Dr. Ormonde Mahoney	706/549-1663 mahoney@aocfoundation.org	
Yang-Chieh Fu, MS	706/542-4132 ycfu@uga.edu	
Tracy Kinsey, MSPH	706/549-1663 tracy@aocfoundation.org	
Dr. Takahiko Kiyama	706/549-1663 wave.kiyataka@excite.co.jp	
Megan Johnson	706/549-1663 mjohnson.athens@gmail.com	
Jao Pom Yom	706-542-4132 jaeyom@gmail.com	
David Kim	706/542-4132 david364@uga.edu	

Additional questions or problems regarding your rights as a research participant should be addressed to The Chairperson, Institutional Review Board, University of Georgia, 612 Boyd Graduate Studies Research Center, Athens, Georgia 30602-7411; Telephone (706) 542-3199; E-Mail Address IRB@uga.edu.

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Item 1.2 (FOR Healthy participant) INFORMED CONSENT FOR RESEARCH PARTICIPATION

I, _____ agree to participate in the research study entitled, "Effects of varus/valgus preoperative deformity on the biomechanics of unicompartmental knee arthroplasty individuals", that is being conducted by Dr. Kathy Simpson (706-542-4385) and Mr. Yang-Chieh Fu (graduate student, 706-542-4132), Department of Kinesiology at the University of Georgia, Athens, GA, and Dr. Ormonde Mahoney (706-549-1663) and Ms Tracy Kinsey (706-549-1663), Athens Orthopedic Clinic, PA. I understand that this participation is entirely voluntary; I can refuse to participate or withdraw my consent at anytime without penalty or loss of benefits to which I am otherwise entitled. I can have the results of my participation, to the extent that can be identified as mine returned to me, removed from the research records, or destroyed. Additionally, if I am ineligible or become ineligible during my participation in the study and am released from further involvement in the study by the researchers, there also are no penalties or financial charges. My decision to participate/not participate or to withdraw my consent at any time if I so choose, will in no way affect any current or future medical treatments that I receive or will receive from Athens Orthopedic Clinic.

The purpose of the study is to investigate the biomechanical factors related to physical function after having had a unicompartmental knee arthroplasty (UKA). We believe that the information gained from this study will help us understand how well the knee functions and how it moves after having this type of knee replacement surgery. We are particularly interested in investigating how the UKA knee performs during high demand daily activities in comparison to knees have not undergone a partial knee replacement, as this is not currently known.

I may benefit by developing a greater understanding of the general benefits of unicompartmental knee arthroplasty, and, if I so desire, my data will be shown to me, and an informal assessment of my performances will be given to me at the end of my testing. If I so request, I can be provided with a more substantial analysis that may be useful to share with my surgeon or physician.

To be eligible, I must be healthy, free from any leg, foot, back or neck pain, or injury having required major medical attention or surgery; and free from any medical condition that is a) not under control or b) not monitored/treated by a medical physician or c) may adversely affect my safety or performance

If I am female, I cannot be pregnant. If pregnant, the radiation procedures may involve risks to the embryo or fetus, which are currently unforeseeable. Thus, if I am female and unsure whether I am pregnant, I will be given a home pregnancy test kit at no cost to me; and I will take the test at a location/time of my choice. It is my responsibility to determine my pregnancy status and the results of pregnancy test must be negative to be eligible to participate. If I choose to take the pregnancy test, I am not required to divulge any personal information about my pregnancy status or the outcomes of the pregnancy test.

My part in this study will last for approximately 2 hours of physical testing and approximately ½ hr, maximum to complete the two questionnaires. The procedures are as follows: Accompanied by a researcher, I will go to the UGA Dept. of Kinesiology's Biomechanics Laboratory, and I will sign this

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to take care of me throughout the testing, including monitoring how I feel and watching me for any signs of discomfort or other problems; and take care of the participant; e) I will tell the researchers immediately if I feel any signs of discomfort, pain, dizziness or other physical symptoms that could influence my health and safety; and f) the researchers will stop testing immediately if any researcher believes that I not be able to perform the tasks safely or that I may be exhibiting symptoms of a physical problem.

Thus, I am informed that I am to tell the researchers immediately if I begin to experience any discomfort, pain, nausea, dizziness or other atypical physical symptoms. Testing will be stopped immediately, and the researchers and I will discuss whether the problem can be resolved and testing can then continue, if I should postpone testing until a later date, or the rest of the testing will be completely discontinued. Although unlikely, discomfort or muscle soreness in the legs may occur for a few days after participation, as can occur due to participating in any new physical activity. The researchers will exercise all reasonable care to protect me from harm as a result of my participation. In the event of an injury as an immediate and direct result of my participation, the researchers' sole responsibility is to transport me to an appropriate facility if additional care is needed. The researchers will not provide any compensation or payment for medical care. As a participant, I do not give up or waive any of my legal rights.

The only people who will know that I am a research participant are members of the research team and the doctor I choose to provide my physician clearance to participate. No identifying information about me or provided by me during the research will be shared with others, except if necessary to protect my rights or welfare (for example, if I am injured and need emergency care); or if required by law. Only research team members who assist with data collection will see me. All of my data will be coded using a participant ID number that is known only to the researchers. As only the reflective markers are visible to the special motion capture cameras, my recorded performances will be confidential and identifiable only by my participant number. The digital video files of my performances of the functional tasks will only be used by the researchers to help them track the marker locations from the other cameras if needed (which is rarely the case). All the rest of the data are non-identifiable. All data, including the electronic video files, will remain in a secured area. Personal health information will not be disclosed and used for any analysis. Only the primary and co-investigators will have access to the master list that identifies me with my participant ID number, as it will be kept secure and separate from other data files. The master list and digital video files will be destroyed when analysis is finished or 10 years from the start date of this study, whichever comes first.

For any further questions about the research please contact: Co-Investigator, Yang-Chieh Fu at 706/542-4132 (ycfu@uga.edu) or Principal-Investigator, Dr. Kathy Simpson at 706/542-4385 (kjsimpsonuga@gmail.com)

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I understand that I am agreeing by my signature on this form to take part in this research project and understand that I will receive a signed copy of this consent form for my records.

My signature _____ **Date** _____
Please sign both copies, keep one and return one to the researcher.

Name of Researcher(s)	Researcher Signature	Date
Dr. Kathy J. Simpson 706/542-4385	kjsimpsonuga@gmail.com	
Dr. Ormonde Mahoney 706/549-1663	mahoney@aocfoundation.org	
Yang-Chieh Fu, MS 706/542-4132	ycfu@uga.edu	
Tracy Kinsey, MSPH 706/549-1663	tracy@aocfoundation.org	
Dr. Takahiko Kiyama 706/549-1663	wave.kiyataka@excite.co.jp	
Megan Johnson 706/549-1663	mjohnson.athens@gmail.com	
Jao Pom Yom 706-542-4132	jaeyom@gmail.com	
David Kim 706/542-4132	david364@uga.edu	

Additional questions or problems regarding your rights as a research participant should be addressed to The Chairperson, Institutional Review Board, University of Georgia, 612 Boyd Graduate Studies Research Center, Athens, Georgia 30602-7411; Telephone (706) 542-3199; E-Mail Address IRB@uga.edu.

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Item 3

**RESEARCH PARTICIPANT AUTHORIZATION FOR USE AND DISCLOSURE
OF PERSONAL HEALTH INFORMATION**

TITLE: "Effects of varus/valgus preoperative deformity on the biomechanics of unicompartmental knee arthroplasty individuals"

SPONSOR: Athens Orthopedic Clinic, P.A.

INVESTIGATORS:

Dr. Kathy Simpson
Dr. Ormonde M. Mahoney
Yang-Chieh Fu
Tracy Kinsey, R. N.
Dr. Takahiko Kiyama
Megan Johnson
Jao Pom Yom
David Kim

SITES:

University of Georgia
Athens Orthopedic Clinic, Athens, GA
St. Mary's Health Care System, Inc.[®], Athens GA

Federal regulations give me certain rights related to my health information. These include the right to know who will be able to get the information and why they may be able to get it. The study doctor must get my authorization (permission) to use or give out any health information that might identify me.

How will my privacy be protected?

If I decide to be in this study, the study doctor and research team will use health data (information) about me to conduct this study. This may include my name, address, phone number, medical history, and information from my study visit. This health data may come from my family doctor or other health care workers.

This information may also include:

- Past and present medical records

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Page 1 of 3

Restricted ☒ Confidential – Limited Access

Item 3

- Research records
- Records about my study visit
- Information obtained during this research obtained from
 - Questionnaires
 - CT scan
 - Videofluoroscopy system
 - Motion capture system with infrared cameras and force platforms
 - Digital video system
- Records about the study equipment

For this study, the AOC researchers will share health data about me with the UGA researchers who have been approved to do this research by the UGA Human Subjects Institutional Review Board that oversees this research.

Information about me and my health which might identify me may be given to the following:

- The University of Georgia researchers. The University of Georgia Institutional Review Board (may only access my protected health information if necessary):
- The Athens Orthopedic Clinic (AOC)
- St. Mary's Health Care System, Inc.®

Once the research team is legally required to provide health data about me with others, Federal privacy law may no longer protect it.

I give my permission to use and share my health information by signing this form. If I do not give this permission, I will not be able to participate in this research study.

My permission to use and share health data about me will end 50 years from the date I sign this form.

I may take away my permission to use and share health data about me at any time by writing to the study physician (Dr. Mahoney). If I do this, I will not be able to stay in this study. No new health data that identifies me will be gathered after that date. However, health data about me that has already been gathered may still be used and given to others as described in this form.

When the study is over, I may write to the study doctor to ask to see health data about me that was collected during the study.

Item 3

Authorization:

I have been given the information about the use and disclosure of my health information for this research study. My questions have been answered. I will be given a copy of this for my records after all necessary parties have inserted their authorization information and signatures below.

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.

AUTHORIZATION SIGNATURES:

Participant's Signature

Date

Legally Authorized Representative Signature
(If applicable)

Date

Authority of Legal Representative to Act for Subject
(If applicable)

Signature of Person Obtaining Authorization

Date

University of Georgia
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 Approved: 2-12-10
 Expires: 2-11-11

UKA study

For researcher use only: PARTICIPANT ID#: _____ UKA limb: L R B DATE: _____
--

CHAMPS Physical Activity Questionnaire for Older Adults

This questionnaire is about activities that you may have done in the past 4 weeks. The questions on the following pages are similar to the example shown below.

INSTRUCTIONS

- If you **DID** the activity in the past 4 weeks:
 - **Step #1** Check the YES box
 - **Step #2** Think about how many TIMES a week you usually did it, and write your response in the space provided.
 - **Step #3** Circle how many **TOTAL HOURS in a typical week** you did the activity.
- If you **DID NOT** do the activity:
 - Check the NO box and move to the next question

Here is an example of how Mrs. Jones would answer question #1: Mrs. Jones usually visits her friends Maria and Olga twice a week. She usually spends one hour on Monday with Maria and two hours on Wednesday with Olga. Therefore, the total hours a week that she visits with friends is 3 hours a week.

In a typical week during the past 4 weeks did you...	
1. Visit with friends or family (other than those you live with)?	How many TOTAL hours a week did you usually do it? →
☒ YES How many times a week? <u>2</u>	Less than 1 hour 1-2.5 hours <u>3-4.5 hours</u> 5-6.5 hours 7-8.5 hours 9 or more hours
☐ No	

In a typical week during the past 4 weeks, did you ...	
1. Visit with friends or family (other than those you live with)?	How many TOTAL hours a week did you usually do it? →
☐ YES How many times a week? ____ →	Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
☐ No	
2. Go to the senior center?	How many TOTAL hours a week did you usually do it? →
☐ YES How many times a week? ____ →	Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
☐ No	
3. Do volunteer work?	How many TOTAL hours a week did you usually do it? →
☐ YES How many times a week? ____ →	Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
☐ No	
4. Attend church or take part in church activities?	How many TOTAL hours a week did you usually do it? →
☐ YES How many times a week? ____ →	Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
☐ No	

5. Attend other club or group meetings? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
6. Use a computer? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
7. Dance (such as square, folk, line, ballroom) (do <u>not</u> count aerobic dance here)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours

In a typical week during the past 4 weeks, did you...	
8. Do wood working, needlework, drawing, or other arts or crafts? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
9. Play golf, carrying or pulling your equipment (count <u>walking time</u> only)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
10. Play golf, riding a cart (count <u>walking time</u> only)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
11. Attend a concert, movie, lecture, or sport event? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
12. Play cards, bingo, or board games with other people? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
13. Shoot pool or billiards ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours

In a typical week during the past 4 weeks, did you...	
14. Play singles tennis (do <u>not</u> count doubles)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
15. Play doubles tennis (do <u>not</u> count singles)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours

16. Skate (ice, roller, in-line)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
17. Play a musical instrument? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
18. Read? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
19. Do heavy work around the house (such as washing windows, cleaning gutters)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
20. Do light work around the house (such as sweeping or vacuuming)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours

In a typical week during the past 4 weeks, did you...	
21. Do heavy gardening (such as spading, raking)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
22. Do light gardening (such as watering plants)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
23. Work on your car, truck, lawn mower, or other machinery? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours

****Please note:** For the following questions about running and walking, include use of treadmill.

24. Jog or run? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
25. Walk uphill or hike uphill (count only uphill part)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
26. Walk fast or briskly for exercise (do not count walking leisurely or uphill) ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours

In a typical week during the past 4 weeks, did you...	
27. Walk to do errands (such as to/from a store or to take children to school (<u>count walk time only</u>)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
28. Walk <u>leisurely</u> for exercise or pleasure? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
29. Ride a bicycle or stationary cycle? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
30. Do other aerobic machines such as rowing or step machines (do <u>not</u> count treadmill or stationary cycle)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
31. Do water exercises (do <u>not</u> count other swimming)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
32. Swim moderately or fast? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
33. Swim gently? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
In a typical week during the past 4 weeks, did you...	
34. Do stretching or flexibility exercises (do <u>not</u> count yoga or Tai-chi)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
35. Do yoga or Tai-chi? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
36. Do aerobics or aerobic dancing? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours

37. Do moderate to heavy strength training (such as hand-held weights of <u>more than 5 lbs.</u> , weigh machines, or push-ups)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
38. Do light strength training (such as hand-held weights of <u>5 lbs. or less</u> or elastic bands)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
39. Do general conditioning exercises, such as light calisthenics or chair exercises (do <u>not</u> count strength training)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
In a typical week during the past 4 weeks, did you...	
40. Play basketball, soccer, or racquetball (do <u>not</u> count time on sidelines)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours
41. Do other types of physical activity not previously mentioned (please specify)? ☐ YES How many times a week? ___ → ☐ No	How many TOTAL hours a week did you usually do it? → Less than 1 hour 1-2.5 hours 3-4.5 hours 5-6.5 hours 7-8.5 hours 9 or more hours

Thank you

UKA 2009

For researcher use only:

PARTICIPANT ID#: _____

UKA limb: L R B

DATE: _____

1

Item 5.1 General Health Status Questionnaire**Instructions:**

- Please respond as completely as possible. Your responses to this questionnaire will be kept confidential and be reviewed only by any of the four main investigators: Dr. Simpson, Dr. Mahoney, Ms. Kinsey, and/or Mr. Fu.
- IF you have had a *knee replacement on both limbs*, for questions regarding your legs and/or knee replacements, please be sure to answer the questions *for both legs* and indicate **R** (for right leg) and **L** (for left leg).

General information

Gender (check correct blank): ____ Male ____ Female

Age: _____ (yrs)

Limb received surgery: L R Both

Knee replacement information: *Answer for the replaced knee (or both knees if you have had both knees replaced):*

Have you had any problems with your operated leg(s) since recovery but not currently?

Circle: Yes No If yes, explain briefly: _____

Are you currently having any problems with your knee replacement(s)?

Circle: Yes No If yes, explain the problem briefly: _____

Health Conditions

1) Please identify how you would evaluate your health overall (circle best choice below)

Excellent Good Fair Somewhat poor Very poor

2) Do you have any current medical problems? Check ALL appropriate boxes. For dates, enter month/year; for example "5/2005".

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3) Have you experienced any of the following conditions within the last week, including today?

(Circle Yes or No)

- a) Balance problems? Yes / No
- b) Nausea, especially during physical activity? Yes / No
- c) Dizziness? Yes / No
- d) Vision problems? Yes / No
- e) Felt uncoordinated, e.g., clumsy, wobbly or shaky? Yes / No
- f) Impaired ability to think or follow directions? Yes / No
- g) Pain/discomfort/other symptoms
- h) Injury/illness/? Yes / No If YES, explain:

4) Currently taking medications (prescription or nonprescription)? Yes / No.

If YES, list all medications.

5) Date of last complete medical exam: _____. Were there any abnormalities or conditions diagnosed that we should be informed about? Yes No If YES, explain

6) Have you ever experienced the following? Place a checkmark under "yes" or "no." If yes, check the relevant body location.

Yes No Broken bone? If so, to: ____ right leg ____ left leg ____ spine ____ intact foot

Yes No Surgery? If so, to: ____ right leg ____ left leg ____ spine ____ intact foot

Yes No Sprain to: ____ right or left hip ____ right or left knee ____ intact ankle

7) Yes No Maybe (Circle) Is there any other information related to your health that we should know to protect your safety and health or that might possibly influence your movements or your ability to complete the tasks? If yes or maybe, explain below:

Other comments (Use back if no spaces):

UKA 2009

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[illegible]

UKA 2009

3

3) Have you experienced any of the following conditions within the last week, including today?

(Circle Yes or No)

- a) Balance problems? Yes / No
- b) Nausea, especially during physical activity? Yes / No
- c) Dizziness? Yes / No
- d) Vision problems? Yes / No
- e) Felt uncoordinated, e.g., clumsy, wobbly or shaky? Yes / No
- f) Impaired ability to think or follow directions? Yes / No
- g) Pain/discomfort/other symptoms
- h) Injury/illness/? Yes / No If YES, explain:

4) Currently taking medications (prescription or nonprescription)? Yes / No.

If YES, list all medications.

5) Date of last complete medical exam: _____. Were there any abnormalities or conditions diagnosed that we should be informed about? Yes No If YES, explain

6) Have you ever experienced the following? Place a checkmark under "yes" or "no." If yes, check the relevant body location.

Yes No Broken bone? If so, to: ____ right leg ____ left leg ____ spine ____ intact foot

Yes No Surgery? If so, to: ____ right leg ____ left leg ____ spine ____ intact foot

Yes No Sprain to: ____ right or left hip ____ right or left knee ____ intact ankle

7) Yes No Maybe (Circle) Is there any other information related to your health that we should know to protect your safety and health or that might possibly influence your movements or your ability to complete the tasks? If yes or maybe, explain below:

Other comments (Use back if no spaces):

APPENDIX B:

MARKER SET

Table B1. Marker locations for each body segment. “L” indicates “left”, “R” indicates “right” side of the body. Total number of markers is up to 36 markers.

Body segment	Label	Location Description
Trunk	LSHO	Left and right acromioclavicular joints
	RSHO	
	LELB	
	RELB	Left and right elbow joint markers
	LWRI	Left and right wrist joint markers
	RWRI	
Pelvis	LASI	Left and right anterior superior iliac spines
	RASI	
	LPSI	
	RPSI	Left and right posterior superior iliac spine
Left and right femur	LTRO	Trochanters: Left and right greater trochanters
	RTRO	
	LTHI	
	RTHI	Left and right anterior upper leg markers
	LLFC	Left and right lateral side of femoral condyles in center
	RLFC	
	LMFC	Left and right medial femoral condyles in center
	RMFC	
Left and right shank	LTT	Left and right tibial tuberosity
	RTT	
	LFH	
	RFH	Left and right fibula head
	LLMA	Left and right lateral malleolus
	RLMA	
	LMMA	Left and right medial malleolus
	RMMA	
Left and right foot	LHEE	Left and right heel (removed in dynamic trials)
	RHEE	
	LHE2	
	RHE2	Addition markers at the lateral side of left and right hind foot
	LFMT	
	RFMT	Left and right fifth metatarsal head
	LNTC	Left and right Navicular tubercle
	RNTC	
	LTOE	Left and right middle foot of distal metatarsal
	RTOE	

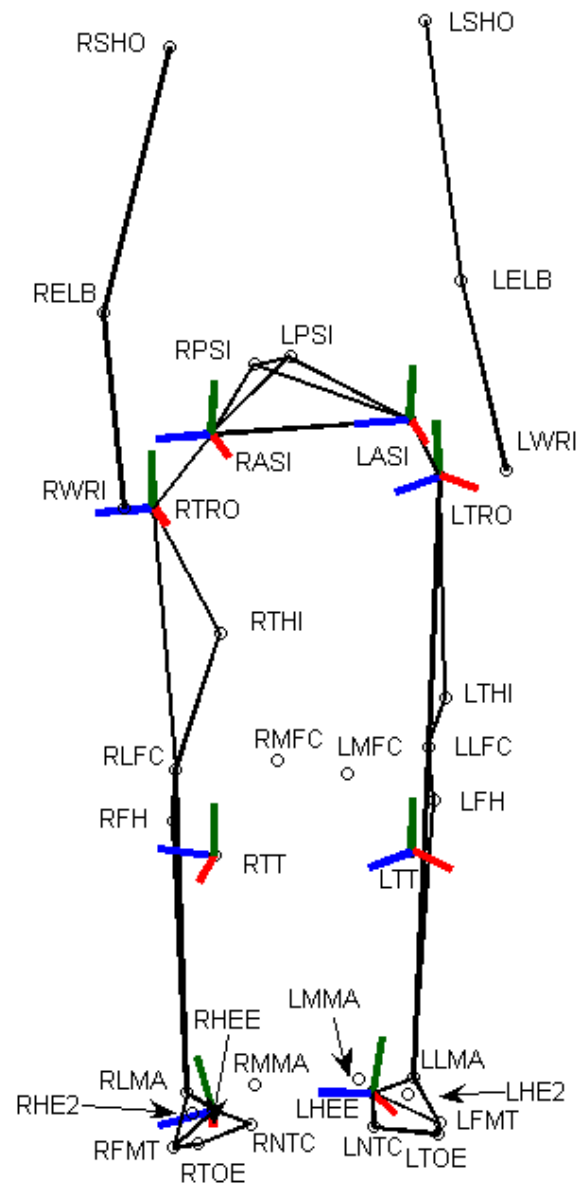


Figure B1 Markers and coordinate systems on the body segments for the upper and lower extremities. Meanings of abbreviations are listed in Table B.1. Positive direction of each local coordinate system is anterior (red, x), superior (dark green, y), and lateral (blue, z) on the right limb and medial on the left limb.

APPENDIX C:

THREE-DIMENSIONAL MOVEMENT ANALYSIS

Movement analysis is a technique that tracks and records skin markers pasted on each body segment using high-speed cameras. A well-defined skin marker set for the human body can help to define proper human body embedded (local) coordinate system from the lab (global) coordinate system, allowing us to calculate joint angles and moments related to three anatomical planes for interpretation. A marker system was used for the lower extremities in the current study (Lu & O'Connor, 1998, 1999). The upper extremities were applied modified VICON[®] plug-in gait model. One AMTI[™] force platform (OR6-6-1[®]: Advanced Mechanical Technology, Inc., Newton, MA) and two Bertec[®] force platforms (FP4060-NC[®]: Bertec, Inc. Columbus, OH) were used to collect ground reaction forces and moments while the lower limb is on the ground and first step of the stairs.

Three-dimensional (3D) movement analysis of the lower extremities has two main parts: kinematics that generates joint movement (joint angle) and kinetics which generates joint forces and moments. The kinematics analysis protocol is divided into four parts, including coordinate system definition, rotation matrix and translation vector calculation, angular velocity and acceleration calculation and extracting rotational angles related to three anatomical planes. The kinetics analysis protocol includes the calculation of the joint centers and anthropometric parameters of the lower extremity, free body diagram analysis of the lower extremities, and reaction force and joint moment calculations. The two parts of analysis were processed based on the marker set described later.

Marker system

A full-body-segment marker set was used in the current study, which had 30 lower extremities markers and 6 upper limbs markers. The marker list was summarized in Table B1. Criteria of those marker locations were suggested by Cappozzo (1995) and take consideration of International Society of Biomechanics (ISB) recommendation (Wu & Cavanagh, 1995) for coordinate system definition:

1. Location must have high repeatability.
2. Have high visibility to all cameras.
3. Any three markers on the body segment are not collinear.
4. The location should involve minimum skin movement artefact.
5. Markers should be easily applied to anatomical coordinate system.

Thus, marker set applied in the study had at least 4 markers in each segment in the lower extremities. Markers were mainly put at the bony landmarks. A static trial during natural standing for each participant was collected, and marker relationships were analyzed to minimize the effect of skin movement artefacts and marker drop-out during dynamic motion (Veldpaus, Woltring, & Dortmans, 1988)

Kinematics

Coordinate system definition

The Cartesian coordinate systems of the lower extremity segments are defined using the marker set described in Appendix B. It follows ISB recommendation (Wu & Cavanagh, 1995), that the posterior to anterior is defined as x axis, the inferior to superior is defined as y axis, and the medial to lateral is defined as z-axis on the right leg. The left leg has an opposite z-axis to the right leg because of the right hand rule. Figure B1 showed an example for current marker set.

At least 3 markers are required to define a 3D coordinate system (Figure C1). Suppose there are three points, namely P_a , P_b and P_c in the space. The vector $\vec{V}_1$ and $\vec{V}_2$ are defined as

Equation 1 and $\vec{U}_1$ and $\vec{U}_2$ are the unit vector of $\vec{V}_1$ and $\vec{V}_2$ respectively.

$$\begin{cases} \vec{V}_1 = \vec{P}_b - \vec{P}_a \\ \vec{V}_2 = \vec{P}_c - \vec{P}_a \end{cases} \dots\dots\dots (\text{Eq. 1})$$

One can select any vector to start defining coordinate system. Here we let the unit vector $\vec{U}_1$ is equal to the unit vector of the x-axis $\hat{x}$ (Equation 2). Then the y axis is defined as the cross product of $\vec{U}_1$ and $\vec{U}_2$ (Equation 3). The unit vector of the z-axis is defined as the cross product of $\hat{x}$ and $\hat{y}$ (Equation 4) and the direction of the axis follows right hand rule.

Eventually, a new orthogonal Cartesian coordinate system is generated.

$$\hat{x} = \vec{U}_1 \dots\dots\dots (\text{Eq. 2})$$

$$\hat{y} = \vec{U}_1 \times \vec{U}_2 \dots\dots\dots (\text{Eq. 3})$$

$$\hat{z} = \hat{y} \times \hat{x} \dots\dots\dots (\text{Eq. 4})$$

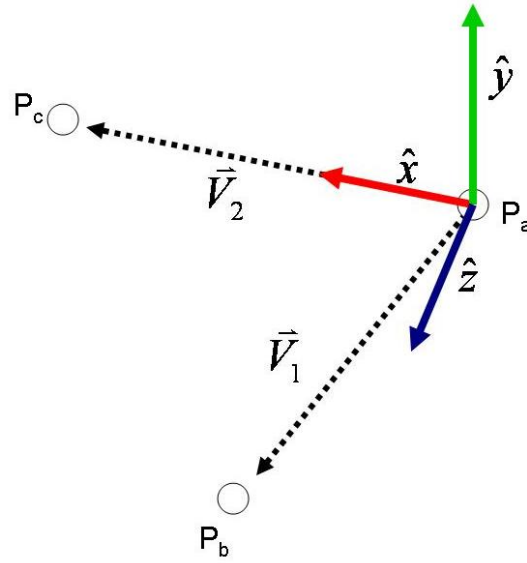


Figure C1 showed the general idea of defining a coordinate system.

Based on this process, local coordinate system for each lower extremity segment is defined.

For the pelvis, the three unit vectors ($\hat{x}_p$, $\hat{y}_p$ and $\hat{z}_p$) of the pelvis axes are defined from

Equation 5 to 7, where $\vec{P}_{label}$ is the position vector of the marker as the labels (see Table B1).

The origin of the pelvis is located on the left and right ASIS (Figure B1) for each leg.

$$\hat{z}_p = \frac{\vec{P}_{RASI} - \vec{P}_{LASI}}{|\vec{P}_{RASI} - \vec{P}_{LASI}|} \dots\dots\dots (\text{Eq. 5})$$

$$\hat{y}_p = \frac{(\vec{P}_{RPSI} - \vec{P}_{RASI}) \times \hat{z}_p}{|(\vec{P}_{RPSI} - \vec{P}_{RASI}) \times \hat{z}_p|} \dots\dots\dots (\text{Eq. 6})$$

$$\hat{x}_p = \hat{y}_p \times \hat{z}_p \dots\dots\dots (\text{Eq. 7})$$

For the thigh (left and right are the same), the local coordinate system ($\hat{x}_t$, $\hat{y}_t$ and $\hat{z}_t$) is defined as Equation 8 to 10. The origin is on the greater trochanter.

$$\hat{z}_t = \frac{\bar{p}_{LEP} - \bar{p}_{MEP}}{|\bar{p}_{LEP} - \bar{p}_{MEP}|} \dots\dots\dots (\text{Eq. 8})$$

$$\hat{x}_t = \frac{(\bar{p}_{GTRO} - \bar{p}_{LEP}) \times \hat{z}_t}{|(\bar{p}_{GTRO} - \bar{p}_{LEP}) \times \hat{z}_t|} \dots\dots\dots (\text{Eq. 9})$$

$$\hat{y}_t = \hat{z}_t \times \hat{x}_t \dots\dots\dots (\text{Eq. 10})$$

For the shank, the local coordinate system ($\hat{x}_s, \hat{y}_s$ and $\hat{z}_s$) is defined as Equation 11 to 13

and the origin is on the tibial tuberosity.

$$\bar{x}_s = \frac{(\bar{p}_{HF} - \bar{p}_{MMA}) \times (\bar{p}_{LMA} - \bar{p}_{MMA})}{|(\bar{p}_{HF} - \bar{p}_{MMA}) \times (\bar{p}_{LMA} - \bar{p}_{MMA})|} \dots\dots\dots (\text{Eq. 11})$$

$$\hat{z}_s = \frac{\hat{x}_s \times [\bar{p}_{TT} - (\bar{p}_{MMA} + \bar{p}_{LMA})/2]}{|\hat{x}_s \times [\bar{p}_{TT} - (\bar{p}_{MMA} + \bar{p}_{LMA})/2]|} \dots\dots\dots (\text{Eq. 12})$$

$$\hat{y}_s = \hat{z}_s \times \hat{x}_s \dots\dots\dots (\text{Eq. 13})$$

For the foot, the local coordinate system ($\hat{x}_f, \hat{y}_f$ and $\hat{z}_f$) is defined as Equation 14 to 16

and the origin is on the heel

$$\hat{x}_f = \frac{(\bar{p}_{NTC} + \bar{p}_{FMT})/2 - \bar{p}_{HEE}}{|(\bar{p}_{NTC} + \bar{p}_{FMT})/2 - \bar{p}_{HEE}|} \dots\dots\dots (\text{Eq. 14})$$

$$\hat{y}_f = \frac{\hat{x}_f \times (\bar{p}_{NTC} - \bar{p}_{HEE})}{|\hat{x}_f \times (\bar{p}_{NTC} - \bar{p}_{HEE})|} \dots\dots\dots (\text{Eq. 15})$$

$$\hat{z}_f = \hat{x}_f \times \hat{y}_f \dots\dots\dots (\text{Eq. 16})$$

Those unit vectors of each body segment of the lower extremities will be used to define rotation matrices of all body segments.

Rotation matrix and translation vector

Relationship between a rigid body in the space and the existing global coordinate system can be described by a rotation matrix and a translation vector. Any point on this rigid body can be represented by the same rotation matrix and translation vector. Let a 3-by-3 rotation matrix R_{l2g} describes the angular relationship between a rigid body A and the global (or lab) coordinate system and a 3-by-1 translation vector $\bar{o}_l$ describe the amount from the origin of the global coordinate system to local one. Then, a point $\bar{p}_l$ on the rigid body A can be described under global coordinate system as:

$$\bar{p}_g = R_{l2g} \bar{p}_l + \bar{o}_l \dots\dots\dots (\text{Eq. 17})$$

$$R_{l2g} = [\hat{x}_l \quad \hat{y}_l \quad \hat{z}_l] \dots\dots\dots (\text{Eq. 18})$$

However, the nine direction cosine of the rotation matrix is not independent. Theoretically speaking, the rotation matrix could be described by three independent variables, which are also called Euler angles or Cardan angles. Therefore, the rotation matrix could be redefined following the rotation sequence (ϕ_i, ϕ_j, ϕ_k) relative to the three axes. That is, the rotation matrix R_{l2g} in Equation 18 could rewrite as:

$$R_{l2g} = R(\phi_i)R(\phi_j)R(\phi_k) \dots\dots\dots (\text{Eq. 19})$$

When i, j and k are not equal, it is called Cardan angles. On the other hand, it is called Euler angles when i = k. Let us use pelvis as an example to clarify the relationship between rotation angles (here using Cardan angle) and rotation matrix. As Figure C2 shows, α , β and γ are three angles of the three axes, which is the same meaning as ϕ_i , ϕ_j and ϕ_k . In Figure C2, x-y-z are symbols used to represent the three axes of pelvis coordinate system while o is the origin, and

capitalized X-Y-Z are lab global coordinate system while O is the origin. Thus, the relationships of the pelvis local coordinate system relative to the global coordinate system are:

$$\bar{x} = (x_X, x_Y, x_Z) \dots\dots\dots (\text{Eq. 20})$$

$$\bar{y} = (y_X, y_Y, y_Z) \dots\dots\dots (\text{Eq. 21})$$

$$\bar{z} = (z_X, z_Y, z_Z) \dots\dots\dots (\text{Eq. 22})$$

where elements in the parentheses are components of the local coordinate system relative to the global coordinate system, the projection, or the direction cosine. Consequently, the rotation matrix R_{l2g} is defined as:

$$R = [\bar{x}, \bar{y}, \bar{z}] = \begin{bmatrix} x_X & y_X & z_X \\ x_Y & y_Y & z_Y \\ x_Z & y_Z & z_Z \end{bmatrix} \dots\dots\dots (\text{Eq. 23})$$

or:

$$R = \begin{bmatrix} \bar{x} \cdot \bar{X} & \bar{y} \cdot \bar{X} & \bar{z} \cdot \bar{X} \\ \bar{x} \cdot \bar{Y} & \bar{y} \cdot \bar{Y} & \bar{z} \cdot \bar{Y} \\ \bar{x} \cdot \bar{Z} & \bar{y} \cdot \bar{Z} & \bar{z} \cdot \bar{Z} \end{bmatrix} \dots\dots\dots (\text{Eq. 24})$$

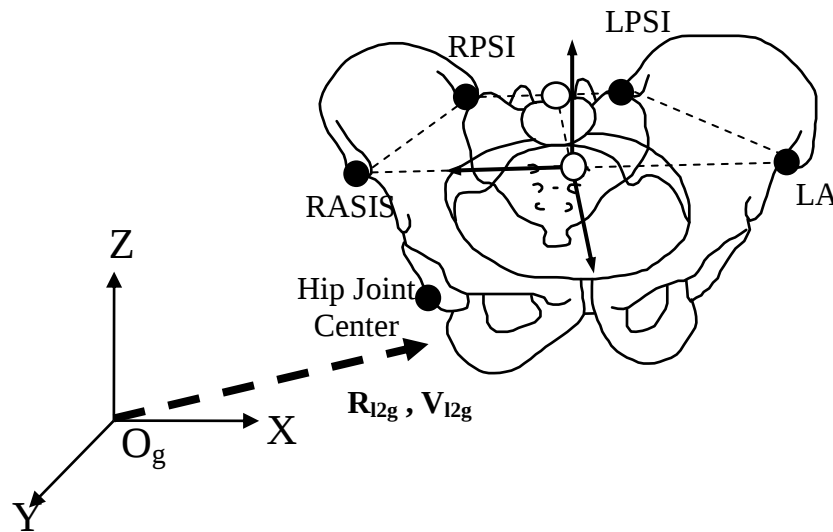


Figure C2 Relationship between local pelvis coordinate system and global (lab) coordinate system. R_{g2l} and V_{g2l} are the rotation matrix and translation vector from global to local.

Rotation matrix can be defined by the vector projection between two coordinate systems. On the other hand, it can also be defined by the three independent variables (Euler or Cardan angles) at a fixed sequence. Considering a coordinate system X-Y-Z is rotated along the Z-axis at γ degrees, a new coordinate system x-y-z is obtained (Figure C3) and the z is coincided with Z (perpendicular to the plane). Let $\vec{p}$ is a vector relative to the X-Y-Z coordinate system, and $\vec{p}'$ is relative to the rotated coordinate system x-y-z. From Equation 24 we know that the projection from x to X is defined as:

$$\vec{x} \cdot \vec{X} = |\vec{x}| |\vec{X}| \cos xX = \cos xX \dots \dots \dots \text{(Eq. 25)}$$

where xX is the included angle of $\vec{x}$ and $\vec{X}$ which equals to γ and the lengths of both $\vec{x}$ and $\vec{X}$ are 1.

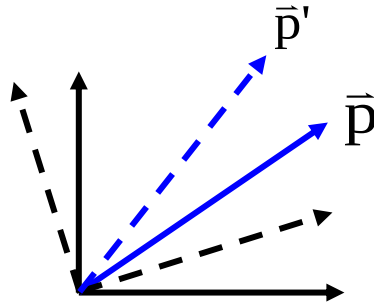


Figure C3 Rotation of the coordinate system. Solid lines are before rotated and dot lines are after rotated.

Therefore, from Equation 24 and 25 and following the same idea described, Equation 24 can be rewritten into:

$$R_z = \begin{bmatrix} \cos_{xX} & \cos_{yX} & \cos_{zX} \\ \cos_{xY} & \cos_{yY} & \cos_{zY} \\ \cos_{xZ} & \cos_{yZ} & \cos_{zZ} \end{bmatrix} \dots\dots\dots (\text{Eq. 26})$$

Since it is only rotated to the Z axis at γ degrees, Equation 26 can be simplified to:

$$R_z = \begin{bmatrix} \cos \gamma & -\sin \gamma & 0 \\ \sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \dots\dots\dots (\text{Eq. 27})$$

Here R_z is the rotation matrix that rotates only along Z and the rotation matrix of X-Y-Z relative to x-y-z. Then, $\bar{p}'$ can be calculated by the following equation:

$$\bar{p}' = R_z \bar{p} \dots\dots\dots (\text{Eq. 28})$$

Following the same protocol, we can conduct the rotation matrices when X-Y-Z rotates α along X and β along Y are:

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha \\ 0 & \sin \alpha & \cos \alpha \end{bmatrix} \dots\dots\dots (\text{Eq. 29})$$

$$R_y = \begin{bmatrix} \cos \beta & 0 & \sin \beta \\ 0 & 1 & 0 \\ -\sin \beta & 0 & \cos \beta \end{bmatrix} \dots\dots\dots (\text{Eq. 30})$$

Rotation order of a rigid body is not exchangeable. Therefore, the rotation sequence must be defined. ISB suggests a rotation sequence, Z-Y-X, for lower extremities. Thus, rotation matrix of a rigid body rotated from the initial position to another position is obtained from Equation 27, 29 and 30, which is:

$$R = R_z R_y R_x = \begin{bmatrix} C\gamma & -S\gamma & 0 \\ S\gamma & C\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C\beta & 0 & S\beta \\ 0 & 1 & 0 \\ -S\beta & 0 & C\beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & C\alpha & -S\alpha \\ 0 & S\alpha & C\alpha \end{bmatrix} \dots\dots\dots (\text{Eq. 31})$$

where C is cosine and S is sine. Expand Equation 31 we can get:

$$R = \begin{bmatrix} C\gamma \cdot C\beta & -S\gamma \cdot C\alpha + C\gamma \cdot S\beta \cdot S\alpha & S\gamma \cdot S\alpha + C\gamma \cdot S\beta \cdot C\alpha \\ S\gamma \cdot C\beta & C\gamma \cdot C\alpha + S\gamma \cdot S\beta \cdot S\alpha & -C\gamma \cdot S\alpha + S\gamma \cdot S\beta \cdot C\alpha \\ -S\beta & C\beta \cdot S\alpha & C\beta \cdot C\alpha \end{bmatrix} \dots\dots\dots (\text{Eq. 32})$$

Comparing Equation 24 and 32, from $R(3,1)$ we get:

$$-\sin \beta = \bar{x} \cdot \bar{Z} \dots\dots\dots (\text{Eq. 33})$$

and from $R(3,2)$ we get:

$$\cos \beta \sin \alpha = \bar{y} \cdot \bar{Z} \dots\dots\dots (\text{Eq. 34})$$

and from $R(2,1)$ we get:

$$\sin \gamma \cos \beta = \bar{x} \cdot \bar{Y} \dots\dots\dots (\text{Eq. 35})$$

Once we know the three rotation angles and the rotation sequence, the rotation matrix is then calculated in the same idea of Equation 31 and 32. On the contrary, if we know the rotation matrix and rotation sequence, the three rotation angles are also known.

Angular velocity and acceleration

Body segment angular velocity and acceleration of a rigid body is required for a dynamic analysis of a rigid body movement in space. For a segment X, the projected components of segmental angular velocity onto the local coordinate axes can be expressed in terms of Cardan angles defined by Equation 33, 34 and 35:

$$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}_X = \begin{bmatrix} 1 & 0 & -\sin \beta \\ 0 & \cos \alpha & \sin \alpha \cos \beta \\ 0 & -\sin \alpha & \cos \alpha \cos \beta \end{bmatrix} \begin{bmatrix} \dot{\alpha} \\ \dot{\beta} \\ \dot{\gamma} \end{bmatrix}_X \dots\dots\dots (\text{Eq. 36})$$

where α , β , and γ are the angles calculated from Equation 33, 34 and 35. By further differentiating to time, the above angular velocity components yield the corresponding components of segmental angular acceleration:

$$\begin{bmatrix} \dot{\omega}_x \\ \dot{\omega}_y \\ \dot{\omega}_z \end{bmatrix}_X = \begin{bmatrix} 1 & 0 & -\sin \beta \\ 0 & \cos \alpha & \sin \alpha \cos \beta \\ 0 & -\sin \alpha & \cos \alpha \cos \beta \end{bmatrix} \begin{bmatrix} \ddot{\alpha} \\ \ddot{\beta} \\ \ddot{\gamma} \end{bmatrix}_X + \begin{bmatrix} 0 & 0 & -\dot{\beta} \cos \beta \\ 0 & -\dot{\alpha} \sin \alpha & \dot{\alpha} \cos \alpha \cos \beta - \dot{\beta} \sin \alpha \sin \beta \\ 0 & -\dot{\alpha} \cos \alpha & -\dot{\alpha} \sin \alpha \cos \beta - \dot{\beta} \cos \alpha \sin \beta \end{bmatrix} \begin{bmatrix} \dot{\alpha} \\ \dot{\beta} \\ \dot{\gamma} \end{bmatrix}_X \dots\dots\dots (\text{Eq. 37})$$

Joint angle calculation

In this study, joint angle was defined by a relative movement of the body segment. For example of knee joint angle, we first calculate the rotation matrices of the thigh and shank, M_{g2t}

and M_{g2s} respectively. Those rotation matrices are from global to local coordinate system. Then we can get the relative rotation matrix of shank relative to thigh as the following:

$$R_{t2s} = R_{g2t}^T R_{g2s} \dots\dots\dots (Eq. 38)$$

Thus, the knee joint angles are calculated from R_{t2s} which represent the relative relationship between thigh and shank by Equation 33 34 and 35.

Kinetics

Joint centers and anthropometric model

Joint centers of the lower extremities are essential and influence the kinetic analysis critically. Joint centers definition can be very complex. However, as a clinical application of 3D movement analysis, convenience of defining joint center has higher priority than accuracy. As an example of hip joint rotation center definition, ISB recommendation suggests functional approach, also as known as rotational approach, and prediction approach. Functional approach (Cappozzo, 1984) is based on the assumption that the thigh is a rigid body and the hip joint center (HJC) is the center of a sphere described by a marker 3D trajectory on the segment. Prediction approach (Bell, Pedersen, & Brand, 1990) uses cadavers and X-ray to define HJC and summarize to a regression equation. Bell (1990) reported that the regression method was more accurate than the rotational method, while Leardini et al. (1999) found that the functional method performed significantly better than any prediction approach. It is still controversy, though prediction approach is easier to apply on kinds of movement analysis.

This study take the consideration of ISB recommendation, the hip, knee and ankle are defined as following:

$$HJC = (-0.19W, -0.30W, 0.36W * i) \dots\dots\dots (Eq. 39)$$

$$KJC = (LFC + MFC) / 2 \dots\dots\dots (Eq. 40)$$

$$AJC = (LMA + MMA) / 2 \dots\dots\dots (Eq. 41)$$

where KJC and AJC are the abbreviation of the knee joint center and the ankle joint center respectively. Equation 39 is suggested by Bell (1990), and W is the width of pelvis which defined by the distance between tow ASIS and *i* is 1 for right leg and -1 for left leg. LFC, MFC, LMA and MMA are femoral condyles markers and malleoli markers.

Anthropometric model is a critical part for human kinetic analysis. The most popular anthropometric parameters information are published by Clauser (1969) and Dempster (1959). Advantages of them are the valid regression equation and are easier to apply. The center of mass (COM), portion of COM relative to segment longitudinal axis, and three principle moments of inertia are calculated based on D. A. Winter's summarized model of each participant (Winter, 2005). Whole body segment including head and neck, upper, middle and lower part of the trunk, upper arm, forearm, hand, thigh, shank and foot are calculated. To apply those parameters onto marker location during movement, the longitudinal axis of each segment needs to be defined by reflected markers. All definitions of each segment are defined in Table C1.

Table C1 Longitudinal axis definition of each body segment of the lower extremity.

Foot	Heel marker to toe marker
Shank	Mid point of femoral condyles markers to the middle point of malleoli markers
Thigh	ASIS to the middle point of femoral condyles markers
Trunk to pelvis	Average of LSHO and RSHO to the mid point of LASI, RASI, LPSI, and RPSI

Free body diagram analysis of the lower extremities

Take free body diagram of the human lower body segment is essential for dynamics of the human movement. Free body diagram is a fundamental skill for mechanical analysis. A rigid body can freely separate into many small segments, and loading condition before and after separation must be equivalent. Each separated small segment also called free body segment. Each free body also needs to keep force and moment equilibrium principle. For example of taking free body diagram of the human shank segment, results are showed in Figure C4. Symbols and equations for calculation are described in next section. All the human body segments can be taken free body similar as Figure C4.

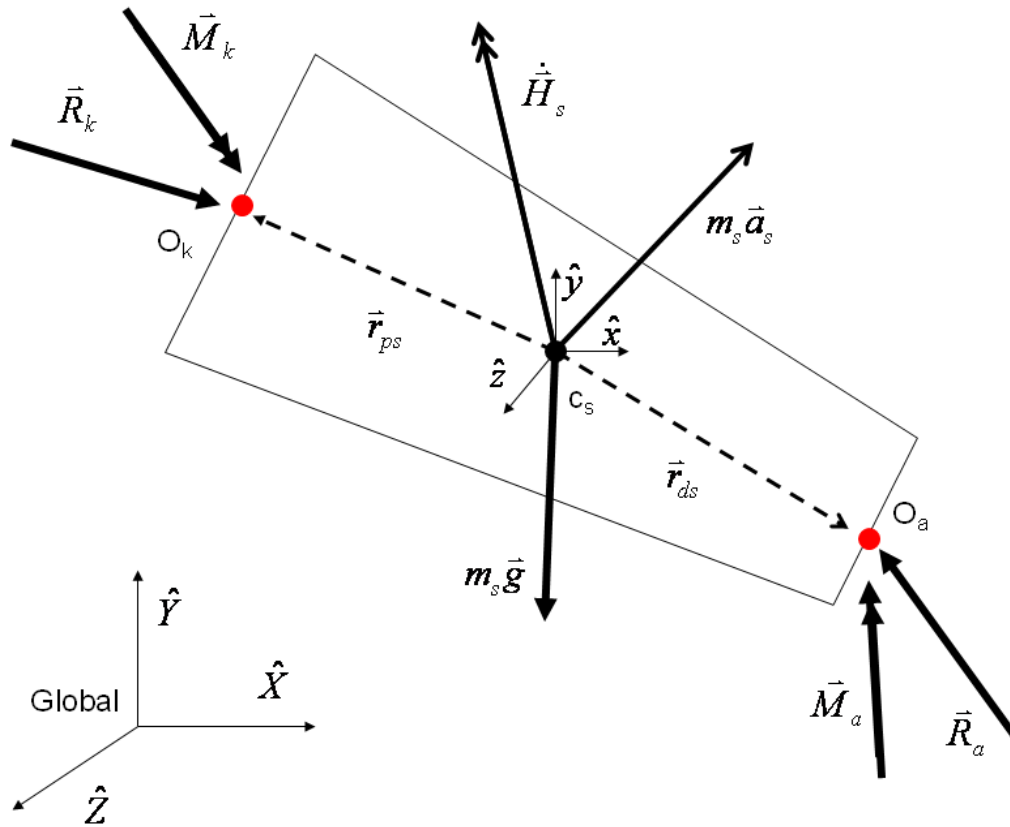


Figure C4 Free body diagram of the human shank segment. O_a and O_k are joint center (red points) of ankle and knee respectively. Symbols are described in content.

Joint reaction force and joint moment

After taking body, joint reaction force and joint moment can be calculated by force and moment equilibrium. First, the angular moment needs to be calculated. Since angular acceleration is obtained from rotation of segment local coordinate system, the angular momentum $\dot{\vec{H}}_q$ of a segment local coordinate system S_q relative to the mass center C_q is differentiate of angular momentum to time:

$$\dot{\vec{H}}_q = J_q \cdot \dot{\vec{\omega}}_q + \vec{\omega}_q \times (J_q \cdot \vec{\omega}_q) \dots\dots\dots (\text{Eq. 42})$$

where J_q is inertia tensor of segment q, including moment of inertia (I_{xx}, I_{yy}, I_{zz}) and product of inertia (I_{xy}, I_{yz}, I_{zx}) as following:

$$J_q = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zx} & I_{zz} \end{bmatrix}$$

$$I_{xx} = \int_M (y^2 + z^2) dm \quad I_{yy} = \int_M (x^2 + z^2) dm \quad I_{zz} = \int_M (x^2 + y^2) dm \dots\dots\dots (\text{Eq. 43})$$

$$I_{xy} = \int_M (xy) dm \quad I_{yz} = \int_M (yz) dm \quad I_{zx} = \int_M (zx) dm$$

where m is small portion of mass, M is total mass, and ω is angular velocity.

If axes of the segment local coordinate system consist with segment geometric axes, product of inertia will be zero. Thus, Equation 43 can be simplified as:

$$\begin{bmatrix} \dot{H}_x \\ \dot{H}_y \\ \dot{H}_z \end{bmatrix}_q = \begin{bmatrix} I_{xx}\dot{\omega}_x + (I_{zz} - I_{yy})\omega_y\omega_z \\ I_{yy}\dot{\omega}_y + (I_{xx} - I_{zz})\omega_z\omega_x \\ I_{zz}\dot{\omega}_z + (I_{yy} - I_{xx})\omega_x\omega_y \end{bmatrix}_q \dots\dots\dots (\text{Eq. 44})$$

After applying Eulerian law, the equilibrium equations of segment mass center C_q relative to global coordinate system can be written as:

$$\sum \vec{M}_q = R_q \dot{\vec{H}}_q \dots\dots\dots (\text{Eq. 45})$$

where $\sum \vec{M}_q$ is the summation of all external moment acting on segment and R_q is rotation matrix of corresponding segment. Also following the linear movement equation of Newton's laws, the force equilibrium equation is:

$$\sum \vec{F}_q = m_q \vec{a}_q \dots\dots\dots (\text{Eq. 46})$$

where $\sum \vec{F}_q$ is the summation of all external force action on segment and $\vec{a}_q$ is linear acceleration of segment.

When we apply Equation 45 and 45 to free body diagrams of the human lower extremities from distal to proximal, or from foot to pelvis, the kinetics of lower extremities are analyzed.

Thus in Figure C4, the equilibrium equations of the shank at the knee joint are:

$$\vec{R}_k = \vec{R}_a + m_s \vec{a}_s - m_s \vec{g}_s \dots\dots\dots (\text{Eq. 47})$$

$$\vec{M}_k = \vec{R}_a \dot{\vec{H}}_s + \vec{r}_{ds} \times \vec{R}_a - \vec{r}_{ps} \times \vec{R}_k + \vec{M}_a \dots\dots\dots (\text{Eq. 48})$$

where $\vec{r}_{ds}$ is the distance from the ankle joint center to center of mass C_s of the shank, and $\vec{r}_{ps}$ is from the knee joint center to C_s . Therefore, the equilibrium equations of the foot at the ankle joint are:

$$\vec{R}_a = m_f \vec{a}_f - m_s \vec{g} - \vec{F}_g \dots\dots\dots (\text{Eq. 49})$$

$$\vec{M}_a = \vec{F}_g \dot{\vec{H}}_f - \vec{r}_{df} \times \vec{F}_g - \vec{r}_{pf} \times \vec{R}_a + \vec{M}_g \dots\dots\dots (\text{Eq. 50})$$

Here $\vec{F}_g$ and $\vec{M}_g$ are ground reaction force and moment measured from forceplate, and $\vec{r}_{df}$ and $\vec{r}_{pf}$ are the lever arm which has similar definition of Equation 47 and 48. The hip joint reaction force and moments are:

$$\vec{R}_h = \vec{R}_k + m_t \vec{a}_t - m_t \vec{g} \dots\dots\dots (\text{Eq.51})$$

$$\vec{M}_h = \vec{R}_k \dot{\vec{H}}_t + \vec{r}_{dt} \times \vec{R}_k - \vec{r}_{pt} \times \vec{R}_h + \vec{M}_k \dots\dots\dots (\text{Eq. 52})$$

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