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Comparison of in vivo human knee joint kinematics using axodes

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COMPARISON OF IN VIVO HUMAN KNEE JOINT KINEMATICS USING AXODES

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

in

The Department of Mechanical and Industrial Engineering

by

Jacob Hipps

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Very special thanks to my parents, wife, and kids for their continual support and love. Thanks to my wife, Alyssa, for all your hard work and understanding during this journey.
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ABSTRACT

The human knee is of particular interest because of its importance in mobility. Pain and stability can be directly related to the motion, or kinematics, of the knee. Many studies have been conducted to quantify human knee kinematics, both in vitro and in vivo. One of the inherent issues with in vivo, skin mounted measurement systems is that they do not account for soft tissue artifact. Compensation for soft tissue artifact has been a difficult challenge for skin mounted tracking systems and has not yet been achieved. Therefore, bone mounted skeletal pins were chosen as the method of gathering kinematic data for this study. Mounting bone pins is not the quintessential method to study motion due to its invasive nature; nevertheless, it provides a great amount of trustworthy, useful insight.

Murphy conducted an in vivo experiment to capture the 3D kinematics of the normal human knee. The kinematic data were used to find the Instantaneous Screw Axis or Instantaneous Helical Axes (IHA). If progressive IHA’s are plotted on the same plot, the surface that is created is called the moving axode of the motion. Several degrees of freedom are needed to accurately describe the kinematics of the human knee during normal movement.

The current study further analyzes the data that Murphy reported in 1990. The goal is to find an effective way to express kinematic information in a coordinate system-independent manner so that comparison is meaningful and feasible between gait/ROM trials, subjects, and knee repair/replacement methods. Axodes were used to compare knee kinematics, trial to trial, for gait, range of motion (ROM), and pivot step.

It was established that 6 independent screws are required to fully describe the motion during gait. Thus, the knee behaves like a 6 DOF mechanism during gait and, therefore, two-,
three-, four-, or five-screw system models are insufficient to adequately and uniquely define the screw system. Screw invariants were found to be a viable option of understanding knee kinematics. Axodes were plotted with pre-stance, stance phase, and post-stance phase indicated. Screw invariants, pitch and moment, were plotted as a function of flexion angle.
1 INTRODUCTION

The human knee joint is a complex system composed of bones, ligaments, cartilage, tendons, and muscles which work in parallel to put a human body in motion. It experiences high loads and impact forces which can stress the system and cause damage to its parts. Often times when these constituents are damaged the ensuing pain and swelling reduce the mobility of the knee and, consequently, the individual. Knee problems can cause compensatory gait which can lead to pain in other areas of the body [1].

Restoration or preservation of knee motion, hereafter referred to as knee kinematics, after repair of ligaments, implantation of a Total Knee Arthroplasty (TKA), or repair of articulating cartilage, is of high importance. If the knee is not reconstructed properly, the kinematics are altered, oftentimes other joints, muscles, and connective tissue of the body.

Murphy conducted an in vivo experiment to capture the 3D kinematics of the normal human knee using a photogrammetric approach: bone mounted markers with an array of Light Emitting Diodes (LED’s) and two Infrared Cameras. The hardware/software collection used to collect data in Murphy’s experiments was the TRACK III (Telemetered Rapid Acquisition and Computation of Kinematic Data) system, which was developed in the Newman Laboratory (MIT, Cambridge, MA). Arrays of LED’s were mounted via skeletal pins to the tibia (shank) and the femur (thigh). The LED’s were fired sequentially at 315 Hz with a system maximum of 30 LED’s (Selspot I Camera Setup). The kinematic data were used to find the Instantaneous Helical Axes (IHA). If progressive IHA’s are plotted on the same plot, the surface that is created is called the moving axode of the motion. Murphy plotted the axodes and found that the loci for the axodes were noticeably different for the three tasks performed: voluntary swing, normal gait, and pivot maneuver. The results bolstered the idea that the human knee cannot be modeled as a
simple pendulum. Several degrees of freedom are needed to accurately describe the kinematics of the human knee during normal movement. Knee kinematic information is useful in reconstructive surgery, artificial joint design/kinematic fitting, and malformed limb reparation.

1.1 Quantifying and Comparing Skeletal Motion

Currently, there is no tried and true in vivo method for quantifying skeletal knee kinematics. Doctors and surgeons base their knowledge of skeletal kinematics on a qualitative method. It is a subjective practice and cannot be readily quantified or compared patient to patient. A laxity test, which tests the looseness of a joint, is one exception to this rule [2]. However, this test focuses on one degree of freedom. In order to understand the motion and the path of the tibia/fibula relative to the femur, six degrees of freedom must be considered. If knee kinematics can be positively quantified and understood, then the design and placement of TKA’s and the function of knee reconstructions will improve. Current methods of quantifying skeletal kinematics are categorized as follows: non-invasive, semi-invasive, and invasive. Each has a different degree of accuracy.

Non-invasive methods typically consist of markers placed on the skin of the subject: reflective markers, LED’s, IMU’s (Inertial Measurement Units – gyroscope and accelerometer combination) [3-6]. These methods are good for general motion, but do not precisely represent the kinematics of the underlying bone [7, 8]. Therefore, there is a tradeoff between accuracy and invasiveness. The less invasive the method, the less accurate the results.

Semi-invasive methods of measuring skeletal kinematics include biplanar videoradiography [9], high-speed sequential biplanar radiography [10], and video fluoroscopy [8, 11]. These methods are classified as semi-invasive primarily because of the extensive x-ray exposure. They are limited by the viewing volumes of their respective x-ray sources and require
a 3D bone model, usually generated by Computed Tomography (CT) and/or Magnetic Resonance Imaging (MRI) [11-13]. Radiation is a bigger factor for methods using CT bone models because CT uses x-rays.

Invasive methods for determining skeletal kinematics are generally the most accurate because the measuring device can be attached directly to the bone: Radiopaque Markers [1, 9], LED’s [7, 14]. In most cases, these methods are less than ideal because they require surgical insertion, they can be painful, and they involve a higher risk of permanent bodily damage. However, because of their accuracy, invasive methods remain the gold standard.

1.2 Objectives

The objectives of these experiments and analyses is to gain a better understanding of human knee kinematics and present the data in a way that transcends both the engineering and orthopedics worlds. Murphy conducted two in vivo experiments where skeletal kinematics of the human knee were collected. Both utilized the TRACK system, located at the Massachusetts Institute of Technology, which consisted of two cameras, a foot force plate, and bone-mounted LED arrays. The results of the first experiment were reported by Murphy in 1990 [14-17]. The results of the second experiment were reported by Liu in 1995 [18] and Fuller in 1997 [7].

The original intent was to compare the two experiments, side by side. Significant progress was made in efforts to retrieve the data from the second experiment. However, a problem was encountered when recreating the processing program; important calibration tables were missing from the backup source that was used. These calibration tables were also stored on a hard disk which is now faulty and cannot be revived. Other backup sources are currently being evaluated and their contents recovered. Obtaining the calibration tables is vital for the complete
recovery of TRACK V data. Therefore, the remainder of this report gives details on both experiments, but new analysis methods will only be applied to the first of the two experiments.

Kinematic comparison of any set of rigid bodies can be accomplished by evaluating translation and rotation. However, these parameters are dependent upon the characteristics of the measurement system: frame of reference, measurement units, and varying definitions of rotation angles and translation directions. It is beneficial to express the motion in way that is independent of the frame of reference, measurement unit, and so forth. Screws and axodes represent the kinematics of rigid bodies in an independent manner [19]. Wolf and Degani were able to identify knee pathologies using screws because of their system independent nature [20]. Different methods of comparing screws, screw systems, and axodes will be discussed hereafter.
2 BACKGROUND

Knee motion can be described or viewed on different levels of complexity. The zeroth order of complexity would describe knee motion using one DOF. This would be equivalent to modeling the knee as a hinge joint, rotating about a point in a planar fashion. Simple designs are easily conceived, but may not perform to the extent that is required for an implantable device. The first order would correspond to a combination of 2 or 3 DOF’s (1 or 2 DOF’s - rotation and 1 DOF - translation); second order would correspond to 6 DOF (rotation and translation in 3D). First order modeling may have been sufficient for early prosthetic design and knee reconstruction, but with the advancement of technology and, subsequently, the depth of knowledge concerning the mechanics of the knee, it is no longer sufficient. The next step in prosthetic knee design and knee reconstruction is to provide higher order designs and reconstructions that allow true knee motion.

Traditionally, infrared and reflective skin-mounted markers and cameras have been used to measure knee kinematics [21, 22]. Inertial Measurement Units (IMU’s), which contain gyroscopes and accelerometers, are also used to quantify knee kinematics [3-6]. These methods produce a macro-scale representation of the motion, but are not accurate enough to provide a micro-scale representation. The problem that most researchers have found is that during skeletal motion, the skin moves relative to the bone. This is referred to as skin motion artifact. Skin motion artifact is the error introduced into the data due to the relative motion of the skin and bone. This relative motion misrepresents the skeletal motion and compensation for this misrepresentation can be difficult [7, 23].
2.1 Human Knee Kinematics

It can be difficult to communicate the six DOF’s that are required to fully define the motion of the knee. One effective way to describe 3D motion is to use instantaneous screws. A screw can be used to describe relative motion, including both 3D translation and 3D rotations. Knee joint translations consist of: 1) Anterior/Posterior Drawer, 2) Medial/Lateral Translation, and 3) Distraction/Compression. Rotations consist of: 1) Flexion/Extension, 2) Internal/External Rotation, 3) Varus/Valgus (deviations) (See Figure 2.1 for definitions)[24]. For further information on screws, see section 3.4.

![Figure 2.1: Six DOF’s of the Human Knee](image)

It is generally accepted that the human knee is a link which has six DOF’s [8]; three of which correspond to 3D displacements and three which correspond to 3D rotation. It is also generally accepted among orthopedists and clinicians that motion between two body segments is reported with the proximal segment as the reference segment and the distal segment as the moving segment (for the present study the femur was used as the reference segment and the tibia was used as the moving segment).
2.1.1 Current Methods of Quantification

You, et al., measured knee kinematics using sequential biplane radiographs in 2001 [12] (See Table 2-1 for summary of current methods). These radiographs were then compared with projections of a Computed Tomography (CT) - generated 3D geometric model. Resultant kinematics were compared with a previously established method: bone-implanted markers. Motion of a canine hind limb was measured during its gait under the aforementioned methods and the differences in measurements were on the order of 0.8 mm for translation and 2.5° for rotation. In 2003, Komistek [11], et al., measured knee kinematics of five normal human knees by way of fluoroscopy and CT scans. 3D models were created from the bone density data recovered from the CT scans. The rate of motion was limited by the video fluoroscopy which had a maximum frame rate of 30 frames per second. The frequency content was then chosen to be 15 frames per second (or motion at about 1-2 km/hr). Differences of 0.55 mm and 0.65° for all translations and rotations were measured between what Komistek reported and the Optotrak method (Northern Digital, Inc., Ontario, Canada) which boasts accuracy of up to 0.1 mm and resolution of 0.01mm. Komistek reported the findings in terms of translations and contact patterns and not in terms of 3D screws. Tashman and Anderst reported the results of skeletal kinematics of ACL deficient canine knees using high speed biplane radiography and CT. Radiopaque markers were employed to synchronize the high speed biplane radiographic images. Intermarker precision had an average deviation of 0.064 mm (distance) and 0.31° (inscribed angles) [10].

Moro-oka, et al., measured human knee kinematics in 2007 using single-plane radiographic projections (X-rays). The X-rays were then shape matched to two different 3D bone models, one of which was created from Computed Tomography (CT), and the other from
Magnetic Resonance Images (MRI). The shape matching routine provided information about the position and orientation of the bones of the joint [13]. The CT model performed significantly better, but the attractive quality of MRI is that there was no radiation exposure involved. However, both methods proved capable of defining knee kinematics with sufficient certainty to differentiate normal and pathological knee motions. Attempts have been made to measure 3D motion of the knee directly from CT and MRI images, but current technology limits this technique to low frame rates [12]. In 2008, van den Bogert, et al, studied the helical axis of human knees during the stance phase of running. A high-speed cine camera was used to track the position of reflective markers mounted to intracortical pins (X-rays were also taken) [1]. In 2010, Akbarshahi, et al, studied the effects of soft tissue artifact in measuring human knee joint kinematics. MRI’s and single-plane fluoroscopic X-ray imaging were used to acquire the skeletal kinematics of the knee [23]. Miranda, et al, used biplanar videoradiography to quantify cadaveric knee joint kinematics of both markerless and marker-based tracking techniques [9]. The experiment showed that markerless and marker-based biplanar videoradiography produced comparable kinematics with markerless only showing a slight reduction in accuracy (0.1 degrees and 0.15 degrees, respectively).

Wolf, et al. [20], created a human knee pathology detection method that utilized the comparison of motion screws. Data were taken via an optical tracking system and instantaneous screw parameters (ISP) were backed out of the data. The concept proposed that when multiple data are recorded for the same motion for a knee with a certain pathology, a cluster of points will form which then can be used to diagnose said pathology. Tests were performed with two models: 1) a Sawbones™ model of the femur and tibia with rubber tubes simulating ligaments and 2) cadaveric right knees. For the Sawbones model, the model predicted the correct pathology with
80% - 90% accuracy depending on the pathology. The results for the cadaveric knees were very similar to the Sawbones, but slightly less accurate [20]. This method looks promising, but it does not account for variability in ligament lengths or insertion sites. The advantage that this method has is that it uses axodes, which are coordinate system independent.

Table 2-1: Current Methods for Acquiring Knee Kinematics

<table>
<thead>
<tr>
<th>Method</th>
<th>Invasiveness</th>
<th>Human or Canine</th>
<th>3D Bone Model</th>
<th>Accuracy Rot.</th>
<th>Accuracy Trans.</th>
<th>Contributor</th>
</tr>
</thead>
<tbody>
<tr>
<td>single-plane radiography</td>
<td>semi</td>
<td>human</td>
<td>CT &amp; MRI</td>
<td>-</td>
<td>-</td>
<td>[13]</td>
</tr>
<tr>
<td>biplane radiography</td>
<td>semi</td>
<td>human</td>
<td>CT</td>
<td>2.5°</td>
<td>0.8mm</td>
<td>[12]</td>
</tr>
<tr>
<td>biplane radiography</td>
<td>invasive</td>
<td>canine</td>
<td>CT</td>
<td>0.31°</td>
<td>0.064mm</td>
<td>[10]</td>
</tr>
<tr>
<td>biplane videography</td>
<td>invasive</td>
<td>human</td>
<td>N/A</td>
<td>-</td>
<td>-</td>
<td>[1]</td>
</tr>
<tr>
<td>biplane videography</td>
<td>non-invasive and invasive</td>
<td>human</td>
<td>N/A</td>
<td>see ¶</td>
<td>see ¶</td>
<td>[9]</td>
</tr>
<tr>
<td>fluoroscopy</td>
<td>semi</td>
<td>human</td>
<td>CT</td>
<td>0.65°</td>
<td>0.5mm</td>
<td>[11]</td>
</tr>
<tr>
<td>single-plane fluoroscopy</td>
<td>semi</td>
<td>human</td>
<td>MRI</td>
<td>-</td>
<td>-</td>
<td>[23]</td>
</tr>
<tr>
<td>optical tracking system</td>
<td>non-invasive (cadaveric and Sawbones™)</td>
<td>human</td>
<td>N/A</td>
<td>see ¶</td>
<td>see ¶</td>
<td>[20]</td>
</tr>
<tr>
<td>optical tracking system</td>
<td>non-invasive and invasive</td>
<td>human</td>
<td>N/A</td>
<td>-</td>
<td>1mm</td>
<td>[7]</td>
</tr>
<tr>
<td>IMU</td>
<td>non-invasive</td>
<td>human</td>
<td>N/A</td>
<td>5°</td>
<td>-</td>
<td>[5]</td>
</tr>
</tbody>
</table>

2.2 The TRACK System

The goal of any biomechanical experiment is to better understand the important function (motion, cooperation, and physical limitations) of any given subsystem of a living being: in this case, the skeletal system of the human being. As these important functions are better defined and modeled, one can begin to formulate ideas and solutions to malfunctioning biomechanical subsystems of the human body. The design requirements and specifications for such solutions are
directly linked to the quality, or integrity, of the experimental results. If the quality of the experimental results is subpar, then conclusions based on the results will be flawed. However, if measures are taken to constrain the system as much as possible and to ensure the resolution of the experimental system, then the amount of error is reduced.

Data collection for this study took place in the Newman Laboratory, Massachusetts Institute of Technology (MIT, Cambridge, MA), using the TRACK system. The TRACK system consisted of: two cameras focused on a point, a force plate, arrays of LED’s used for tracking (Figure 2.2: Location of LED arrays), and a data collecting computer. The cameras took real time \((u,v)\) position coordinates from the cameras’ detector. These coordinates were then sent to a program which calculated \((x,y,z)\) global position coordinates. The LED’s were fired sequentially at high frequency (10 kHz). Therefore, if there were 32 LED’s, then LED 1 would have fired at a frequency of about 312 Hz. The number of segments, varied with the number of LED’s. Segments were used to redundantly obtain motion of at least 3 points on a body. If the detector showed multiple light sources or if the intensity was too high or too low, that particular frame was flagged and removed from the data set. The detector averaged images so the image would be taken from a reflection. TRACK III used a Selspot I camera (1024x1024 resolution detector) and TRACK V used a Selspot II camera (4096x4096 resolution detector). Calibration tests were conducted using an x-y plotter to correct error introduced by the curvature of the camera lenses. Data was collected for 5 segments (: Segment Identification).
Figure 2.2: Location of LED arrays for 1st Experiment

Figure 2.3: Segment Identification for 1st Experiment
2.3 Experiments

Two sets of human knee kinematic experiments took place in the Newman Laboratory at MIT (Cambridge, MA). Both of which utilized the aforementioned TRACK system and were taken from two different healthy human subjects, *in vivo*. Healthy in this sense refers to no known knee pathology, pain, or abnormalities. The first experiment was conducted, analyzed, and reported by Murphy [14]. The second was conducted by Murphy, but was only partially analyzed and reported (1997 in Human Movement Science [7] and in Liu thesis [18]). The major objective was to analyze and report the data of the second experiment and draw conclusions based on the comparison of the two experiments using modern computational and mathematical tools.

The first of the two sets of experiments was reported in 1984 in the proceedings of the Orthopedic Research Society (ORS) and in 1990 in the proceedings of the ASME International Mechanical Engineering Congress and Exposition (IMECE). This set of experiments included the following tasks: 1 - Static, 2 - Ankle Range of Motion (ROM), 2 - Knee ROM, 2 - Hip ROM, 5 - Gait, and 3 - Pivot Step. The six DOF kinematics of the knee were measured and compared using instantaneous helical axes (IHA). When these IHA’s are plotted over time, a ruled surface, called an axode, is generated. The shape of the axode uniquely characterizes the motion of the knee.

The second of the two sets of experiments took place in 1992. This set of experiments included the following trials: 1 – Static, 4 - ROM for Knee, 1 – ROM for Ankle, 9 – Swing, 13 – Gait, 8 - Stationary Bicycle, 6 – Squat, and 2 - Stair Climb.

It is important to note that ROM is not equivalent to the swing phase of gait. Swing is reported in the gait trials and should not be confused with the ROM trials of the knee. However, both are important when analyzing and comparing knee kinematics of different people. The
Squat, Stationary Bicycle, and Stair Climb activities were chosen for their repeatability and the feasibility of capturing the full range of motion.
3 KINEMATIC DEFINITIONS

3.1 Rigid Body Motion

Kinematics is the study of the motion of points in space. A rigid body is defined when the distance between any two points of that body remains constant. Two or more rigid bodies form a mechanism when connected by joints that constrain their relative motion [25]. Applying this concept to the human knee, the leg becomes the mechanism. The mechanism is comprised of two rigid bodies: the femur and tibia/fibula. The knee joint acts as the joint which constrains the relative motion between the femur and the tibia. The relative motion, or relative kinematics, of these two rigid bodies is of interest at present.

3.2 Relative Kinematics

Relative kinematics, or relative motion, of the human knee lends insight into what part of the knee might be unhealthy and how it affects overall knee performance. In 1983, Grood and Suntay proposed an approach to representing kinematic data that would bridge the gap in communication between engineers and clinicians. The approach converts measured joint kinematics to clinically defined motion (displacements and rotation angles) [24].

The approach that Grood and Suntay presented is comprised of: 1) fixed coordinate frames on both the tibia and femur, 2) a translation reference point, and 3) a Cartesian coordinate system fixed to the body which is used to describe the shape of the bone. These three system definitions are imperative in order to retrieve the 3D relative motion of the linkage. Grood and Suntay outline a method to convert the data collected from a dependent, varying coordinate system to clinical rotations and translations such as Flexion/Extension, Varus/Valgus, Internal/External Rotation, Anterior/Posterior Drawer, Medial/Lateral Displacement, and Distraction/Compression (Figure 2.1). The motion is calculated and reported in a composite
manner, meaning that it is not reported as a sequence of individual component rotations or translations. Therefore, the knee can perform a number of rotations and translations simultaneously and the components of the kinematics are measured concurrently. Some have raised the argument that the angles that Grood and Suntay published are simply Euler angles. For further details on the calculation of the clinical translations and rotations, see [24].

### 3.3 Quaternions

In order to describe rigid body motion in 3D, a combination of translations and rotations must be used. A three parameter description of rotation, such as Euler angles, contains singularities – 3D positions can be attained by more than one sequence of the three parameters. Quaternions are 4 parameter descriptors of rotation which are singularity free (although the negative of a quaternion produces the same transformation as its positive). Vectors are used to represent the translations (3 DOF) and quaternions are used to represent the rotations (3 DOF). A quaternion is composed of 4 components,

\[
q = ai + bj + ck + d
\]  

(3.1)

where a, b, c, and d are real magnitudes and i, j, and k are unit vector components. The last variable, d, is a scalar component which has a multiplier of 1. The typical rules of vector algebra do not apply to quaternions due to the fact that it is a combination of a vector and a scalar. Therefore, a new set of algebraic rules, Clifford algebra, must be utilized [25]. Addition/subtraction of two quaternions is accomplished in a similar manner to the addition/subtraction of vectors plus the addition/subtraction of the last component, d. For multiplication, the rules are as follows:
In order to perform quaternion multiplication, the quaternion must be broken up into two components:

\[ q = q_v(\text{vector}) + q_s(\text{scalar}) \]  

(3.4)

where \( q_v \) and \( q_s \) are defined in Equations 3.5 and 3.6:

\[ q_v = ai + bj + ck \]  

(3.5)

\[ q_s = d \]  

(3.6)

Once the quaternion is broken up, the quaternion product of \( q_1 \) and \( q_2 \) can be found by the following equation (Equation 3.7)

\[ q_1q_2 = q_s_1q_{s_2} - q_{v_2} \cdot q_{v_2} + q_{v_1} \times q_{v_2} + q_{s_1}q_{v_2} + q_{s_2}q_{v_1} \]  

(3.7)

The conjugate of \( q \), which is designated by \( q^\dagger \), is defined:

\[ q^\dagger = -ai - bj - ck + d \]  

(3.8)

A position vector, \( R \), and unit norm of a quaternion, \( qq^\dagger \), are used to calculate a rotation, \( R' \), about a point.

\[ qq^\dagger = 1 \]  

(3.9)

\[ R' = qRq^\dagger \]  

(3.10)
Therefore, a rotation in 3D space can be classified by a quaternion if the initial and final positions of a point are known in a global reference frame. Quaternions can be found from a fixed, global reference frame. A relative quaternion can be calculated by performing a transformation using quaternion multiplication. Murphy [14] gives a concise and accurate review of quaternions.

3.4 Screw and Helical Axes

Screws are defined by the theory that any rigid body motion can be described by a rotation about an axis and a translation along that same axis. Consider a disk spinning about its center with no translation in 3D space (Figure 3.1: Screw of a Stationary Disk). The screw associated with this motion would simply be the axis of rotation. One of the benefits of using screws is that an alternative reference frame can be chosen. In the case of knee kinematics, the motion of one segment (the shank) can be classified with respect to another segment (the thigh). Screws are reported in the form of a dual number, part of which is real and part of which is imaginary. Velocity screws are used to calculate the instantaneous helical axis, which is composed of two vector parts: 1) angular velocity of the body and 2) translational velocity of the body.

\[
\mathbf{\gamma} = \mathbf{\Omega} + \mathbf{\varepsilon V} \tag{3.11}
\]

The velocity screw is a dual number having the property \( \mathbf{\varepsilon}^2 = 0 \).

![Figure 3.1: Screw of a Stationary Disk](image)
3.5 The Axode

When a sequence of IHA’s of a rigid body motion is plotted over time, two ruled surfaces, called an axodes, are created. To illustrate this, consider a disk rolling on a horizontal plane (See Figure 3.2: Axode of Disk Rolling without Slipping). Its IHA is located where the disk’s surface contacts the table at all times. However, the disk is moving horizontally, therefore, over time, a ruled, flat surface is created. This ruled flat surface is the fixed axode of the disk which fully conveys its 3D motion. The moving axode is in the moving frame. At any instant the moving frame and the fixed frame share one IHA. The relative motion of the two bodies is the invariant.

![Figure 3.2: Axode of Disk Rolling without Slipping](image)

3.6 Bases for Vectors in Vector Spaces

A basis for a vector space is a set of linearly independent vectors which span the vector space. If a basis can be identified for a given set of vectors, then it can be said that any vector within that
set of vectors is a linear combination of one or more of the basis vectors. A vector set (Equation 3.11) is said to be linearly independent if the vector equation (Equation 3.13) has only one solution (Equation 3.14) [26].

\[ V = \{v_1, v_2, ..., v_n\} \] (3.12)

\[ c_1 v_1 + c_2 v_2 + \cdots + c_n v_n = 0 \] (3.13)

\[ c_1 = c_2 = \cdots = c_n = 0 \] (3.14)

The rank of a set of vectors signifies the quantity of linearly independent vectors. A set of vectors (Equation 3.12) in a vector space, \( \mathbf{VS} \), is said to span \( \mathbf{VS} \) if every vector in \( \mathbf{VS} \) is a linear combination of \( v_1, v_2, ..., v_n \) [26]. Therefore, a basis for a set of vectors is a set of linearly independent vectors that span the vector space [27].

Basis vectors can be compared by plotting them or by taking the inner product. The inner product of the basis of one system versus another system will determine how the two bases are related. Screws are analogous to vectors, meaning they both describe motion in 3D space. Therefore, the principles of basis vectors can be applied to screws - basis screws.

### 3.7 Principal Screws

A screw system is a collection of screws produced by a particular system (joint, rigid body in space, mechanism, or robot manipulator). The number of linearly independent screws in the set equals the number of degrees of freedom [28]. Any screw within the screw system can be obtained by linearly combining a combination of the linearly independent screws that define the screw system [29]. Therefore, any set of linearly independent screws is sufficient to define the screw system. One way to find linearly independent screws that define the system is to find the system’s principal screws. Principal screws are the screws whose pitches are the extremes of the
system as a whole. The number of extreme pitches equals the order of the system [28]. The principal screws of a system disclose information about the system, such as singularities, the instantaneous stability of the workspace, and its mobility [29]. Zhao, et al, defined first- and second-order systems by referring to Hunt and, originally, to Ball [28]. A first-order system is one that has a rank of one and requires only one principal screw to define the system. A second-order system is one that has a rank of two and requires two principal screws to define the system. Similarly, a third-order system is one that has a rank of three and requires three principal screws to define the system. Principal screws and principal pitches for screw systems of higher rank \((n \leq 5)\) can be obtained using the third-order system approach based on reciprocal screw theory. This can be accomplished because systems of higher order can be equivalently transformed into the principal screws formed by its reciprocals, whose order is less than three [30].

Zhao specifies that unit screws have to be used in this method so that the screws can be compared one with another [29]. The unit screw is represented as

\[ s_u = u + \epsilon u_0 \]  

(3.15)

where \( u \) is the direction ratios of the screw axis and \( u_0 \) is the moment part of the screw. These are found by

\[ u = \frac{\Omega}{|\Omega|} \]  

(3.16)

\[ u_0 = \frac{\Omega \times \dot{r} \times \Omega}{|\Omega|} + r \times \frac{\Omega}{|\Omega|} \]  

(3.17)

where \( \Omega \) is the angular velocity vector, \( \dot{r} \) is the velocity vector, and \( r \) is the position vector. Each unit screw occupies a column in \( s_u \), creating a 6xn matrix (where \( n \leq 3 \)). The Gram-Schmidt
orthogonalization process was then employed to ensure that the selected screws are orthogonal. The Gram-Schmidt matrix, \( O \), leads to the eigenvalue matrix \( M_O \), where

\[
M_O = O^T E O
\]  

(3.18)

and

\[
E = \begin{bmatrix}
0_{3\times3} & I_{3\times3} \\
I_{3\times3} & 0_{3\times3}
\end{bmatrix}
\]  

(3.19)

where \( E \) is filled with zeros and ones. To find the eigenvalues of the eigenvalue matrix the following polynomial equation was used

\[
|M_O - 2h_p I_{3\times3}| = 0
\]  

(3.20)

where \( h_p \), the eigenvalues, are the pitches of the principal screws. The eigenvectors associated with the eigenvalues form a matrix \( Q \). The principal screws are then found by multiplying \( O \) with \( Q \). Therefore, the principal screws are

\[
S_p = OQ
\]  

(3.21)

The application of the method introduced by Zhao, et al, utilized three random screws at a time, chosen from the screw system to calculate one set of principle screws. As long as the system has rank \( \leq 3 \), the eigenvalues (pitches) are unique to the system and will be consistent no matter which screws are selected to find the principal screws. These principal screws can be used to compare one screw system to another. If the pitches are alike, the motion of the systems is similar.
3.8 Invariants and Comparison of Motions

Invariants are system defining characteristics that uniquely describe the relative motion of two or more bodies. There are four invariants that are used in these experiments that characterized the system: the angular velocity about the screw axis, the translational velocity along the screw axis, the pitch (the ratio of the translational velocity along the screw axis to the angular velocity about the screw axis), and the moment (the component of translational velocity perpendicular to the screw axis). Invariants are used to compare one screw system to another.

The magnitude of the angular velocity about the screw axis, $\Omega_s$, and the magnitude of the translational velocity along the screw axis, $V_s$, are found by

$$\Omega_s = |\Omega|$$  \hspace{1cm} (3.22)

$$V_s = \frac{\Omega \cdot V}{|\Omega|}$$  \hspace{1cm} (3.23)

The pitch, $h$, and moment, $m$, are found by

$$h = \frac{\Omega_s}{V_s}$$  \hspace{1cm} (3.24)

$$m = \frac{\Omega \times V \times \Omega}{|\Omega|^3}$$  \hspace{1cm} (3.25)
4  DATA ACQUISITION AND PROCESSING

4.1 Data Acquisition

Both knee kinematic experiments were carried out in two sessions with a one hour break in between: skin-mounted markers (2.5hrs for experiment one) and surgical pin-mounted markers (2.5hrs for experiment one). See Table 4-1 for more information. Experiment two took much longer than the first due to the addition of different knee motions (bike and squat motions – See Table 4-2 and Table 4-3). Each session consisted of trials that recorded the motions of interest. At the beginning of each session, a static test was performed to ensure that all LED’s were functioning properly and were in the viewing volume. In an effort to keep motion as natural and painless as possible, Lidocaine (0.1%) was injected at each of the surgical pin locations prior to their insertions and as needed throughout the experiment.

<table>
<thead>
<tr>
<th>Table 4-1: Experiment Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time duration per trial (sec)</td>
</tr>
<tr>
<td>Experiment 1</td>
</tr>
<tr>
<td>Experiment 2</td>
</tr>
</tbody>
</table>

The following tables summarize the trials that were conducted in each of the experiments:
## Table 4-2: First Experiment – Pin Trials

<table>
<thead>
<tr>
<th>File</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>14MA30</td>
<td>Static</td>
</tr>
<tr>
<td>14MA31</td>
<td>Ankle ROM</td>
</tr>
<tr>
<td>14MA32</td>
<td>Knee ROM</td>
</tr>
<tr>
<td>14MA33</td>
<td>Hip ROM</td>
</tr>
<tr>
<td>14MA34</td>
<td>Gait</td>
</tr>
<tr>
<td>14MA35</td>
<td>Gait</td>
</tr>
<tr>
<td>14MA36</td>
<td>Gait</td>
</tr>
<tr>
<td>14MA37</td>
<td>Gait</td>
</tr>
<tr>
<td>14MA38</td>
<td>Gait</td>
</tr>
<tr>
<td>14MA47</td>
<td>Pivot</td>
</tr>
<tr>
<td>14MA48</td>
<td>Pivot</td>
</tr>
<tr>
<td>14MA49</td>
<td>Pivot</td>
</tr>
<tr>
<td>14MA50</td>
<td>Ankle ROM</td>
</tr>
<tr>
<td>14MA51</td>
<td>Knee ROM</td>
</tr>
<tr>
<td>14MA52</td>
<td>Hip ROM</td>
</tr>
</tbody>
</table>
Table 4-3: Second Experiment – Pin Trials

<table>
<thead>
<tr>
<th>Static Trial</th>
<th>ROM Trials</th>
<th>Swing Trials</th>
<th>Gait Trials</th>
<th>Bicycle Trials</th>
<th>Squat Trials</th>
<th>Stair Climb Trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST01</td>
<td>RM01</td>
<td>SW21</td>
<td>NG01</td>
<td>AS01</td>
<td>SQ01</td>
<td>SC01</td>
</tr>
<tr>
<td>RM02</td>
<td>SW22</td>
<td>NG02</td>
<td>AS03</td>
<td>SQ02</td>
<td>SC02</td>
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</tr>
<tr>
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<td>SW23</td>
<td>NG05</td>
<td>AM01</td>
<td>SQ03</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>SW24</td>
<td>NG06</td>
<td>AM02</td>
<td>SQ04</td>
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<td></td>
</tr>
<tr>
<td>RM05</td>
<td>SW25</td>
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<td>AF01</td>
<td>SQ05</td>
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<tr>
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<td>BS01</td>
<td>SQ06</td>
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<td>BM01</td>
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<td>SG01</td>
<td>FM01</td>
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<td>FG01</td>
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<td></td>
<td></td>
<td></td>
<td>FG05</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
4.2 Data Processing

When the data were first collected, three different programs were used to process the data. The first program, which collected the raw data, converted it to quaternions, and performed a smoothing routine, was written in FORTRAN (FORTRAN 77, IBM, San Jose, California) for TRACK III or C (Bell Labs, Berkeley Heights, New Jersey) for Track V. For Track III, the second program, which converted the data into clinical rotations, relative motion, and prepared it for plotting, was written in FORTRAN (FORTRAN 77, IBM, SAN JOSE, CALIFORNIA). For Track V, the second program was written in the C (Bell Labs, Berkeley Heights, New Jersey). For TRACK III, the last program, which was used to create plots of the data, was utilized NCAR (National Center for Atmospheric Research, Boulder, Colorado) plotting techniques. TRACK V was written in OpenGL (Silicon Graphics Inc., Mountain View, California).

The current study uses the FORTRAN (FORTRAN 77, IBM, SAN JOSE, CALIFORNIA)/C (Bell Labs, Berkeley Heights, New Jersey) program (Level One Processing), but combines the second and third programs into one (Level Two Processing). This program was developed in Matlab (R2010a, Mathworks, Natick, Massachusetts). It has the versatility to handle both tasks and reduces processing time. Matlab (R2010a, Mathworks, Natick, Massachusetts) is also used to find and compare the basis vectors of the axodes (Level Three Processing). The details of data processing will be discussed in further detail below.

4.2.1 Level One Processing

Level one processing contains the programming that sets up, calibrates, records the raw data, and returns data in a usable format (translations and rotations). This is accomplished by the following process: 1) Convert camera intensities to camera coordinates, 2) Window bad data, 3) Correct camera non-linearity locations, 4) Check skew-ray error, 5) Convert camera coordinates
to 3D point data, 6) Smooth the data, 7) Calculate 3D point data to rigid body data, 8) Calculate the orientation quaternions based on 3D LED data [31].

The camera raw data (intensity) was recorded to a raw data file. The first step in processing this data was to convert the intensity levels to camera detector coordinates \((u,v)\). The camera coordinates were then sent through a filter to remove the effects of ambient light.

At this point in the processing, the user either chose to “window” the data or not. Windowing the data removes the beginning and end of the data that do not represent the motion of the subject. A camera correction table that was previously created was used to correct the non-linear errors that the camera lens added to the data.

From the \((u,v)\) coordinates, a ray can be traced from each camera to the perceived location of the LED in space. If there were no perception errors, the rays from each camera would intersect at the true location of the LED. However, because of perception errors, the rays are skew (Figure 4.1: Skew-ray Error). A skew-ray error value was calculated and compared with an allowable skew-ray error. If the skew-ray error was above the maximum allowable value, the data point was flagged as bad and had no further processing. The LED’s that had skew-ray error values below the set point, which was 20 units, were then assumed to lie on the perpendicular created by the perceived locations, half-way between each perceived location.

The LED’s were situated with known geometry arrays screwed on to each bone pin. If an LED was perceived to be too far from the other LED’s in the array (i.e. distorted), then that LED was omitted from any further processing. This error was named inter-LED error. The 3D point data for each LED were then calculated for each remaining “good” data and smoothed using the Dohrmann, Busby, and Trujillo smoothing routine [32].
The smoothing routine is applied to the 3D LED coordinates and not to the rigid body data because if the rigid body data were smoothed valuable information would be lost.

The rigid body data (body fixed data) were then calculated from the LED 3D coordinates. Orientation quaternions were calculated using the Schut algorithm [33] and the resultant data were stored in data file. For selection of processing parameters, see Karlsson [34].

4.2.2 Level Two Processing

This level of processing started off by differentiating the rigid body data provided by level one processing. Then a plot parameter selection menu allows the user to select which component, segment, dependent variable, independent variable, derivative, axode, reference frame to plot. The translations and rotations were derived from the position/quaternion matrices and the desired data matrices were sent to the plot command within Matlab (R2010a, Mathworks, Natick,
Massachusetts). Multiple components and/or segments and/or trials can be plotted on the same plot. Finally, the data for the axode for the selected trial is sent to a data file.

4.2.3 Level Three Processing

The data from level two processing was then analyzed for basis screws, or principal screws, of the axode using Matlab (R2010a, Mathworks, Natick, Massachusetts). Multiple trials were loaded in order to compare a trial side by side. The purpose of this comparison was to attempt to find a correlation between the basis/principal screws of like trials and a contrast between dissimilar trials.
5 ERROR ANALYSIS

It is important to consider all possible sources of error in order to assign a level of confidence to the data produced. System errors can propagate and, ultimately, cause the output data to misrepresent the actual behavior of the system. When the system is misrepresented, any conclusions based on the inaccurate data will be invalid and misleading. Therefore, it is imperative to analyze the system as a whole and find potential sources of error. The aforementioned experiments contained instrumentation error and smoothing error. Trials with obvious user/human error were thrown out.

5.1 Instrumentation Error

Instrumentation error is a type of error that is introduced by way of variance in the precision and accuracy of the instruments used to collect the data (i.e. – LED’s, camera lenses, alignment of cameras). Trials where an LED was unplugged or out of view were flagged and processed accordingly. If too many LED’s were missing from the trial, the trial was thrown out. LED arrays were used to calculate the location of the bone pin in \((u,v)\) camera coordinates. The camera detected light intensity of the light sources (LED’s) and therefore the exact position of a single LED might be distorted. However, when an array of LED’s is used, the distance between the LED’s can be used to derive a more accurate location of the bone pin. The error between LED’s is referred to as the Inter-LED error and was less than 25% for all trials. An algorithm, the Schut Algorithm, designed to find the location of a point based on surrounding points was used [35].

Another potential source of error included the curvature of the camera lens. Data points near the corners of the image plane of the camera proved to be misrepresented. In order to correct these data points, a dot matrix plot was created and used to calibrate the \((u,v)\) coordinates
Skew-ray error was introduced as part of a two camera system. The error was introduced by the representative \((u,v)\) coordinates of the cameras. From the \((u,v)\) coordinates in the image plane, a ray can be traced from each camera to the perceived location of the LED in space. If there were no perception errors, the rays form each camera would intersect at the true location of the LED. However, because of perception errors, the rays are skew. A series of tests were conducted by Murphy to determine the maximum allowable skew-ray error, which in this case was 20 units. If the skew-ray error was above the maximum allowable value, the data point was flagged as corrupt. The LED’s that had skew-ray error values below the set point, 20 units, were then assumed to lie on the perpendicular created by the perceived locations, half-way between each perceived location.

5.2 Smoothing Error

Experimental data is inherently noisy and contains unwanted information. Noise is not much of a concern if it is at a much higher frequency than the content which is desired. However, noise can cause many problems when the data is differentiated with respect to time. This was the case of the current experiment. Velocities and accelerations were computed based on the position and orientation data recorded. Therefore, it was necessary to reduce the noise of the data by smoothing. Murphy [14] utilized a smoothing routine by Dohrmann [32] with a derivative criterion of two. Any differentiation took place after the smoothing routine was applied.
6 RESULTS AND DISCUSSION

6.1 Gait Trials of Experiment One

6.1.1 Tibial Rotation versus Percent Gait

Five gait trials of the right leg were recorded for experiment one. The results are presented in terms of percent of Gait (See Figure 6.1 through Figure 6.18). The green box marks heel strike and the red X denotes toe off. Please note that Trial 5 does not represent a full cycle of gait and, therefore, will appear slightly different at first glance.

Flexion/Extension rotation results show consistency between all trials (See Figure 6.1 through Figure 6.6). Trial 1 shows a minimum flexion of about -2° while all other trials show a minimum flexion of about 10° - 14° (See Figure 6.6). This is most likely related to the comfort level of the subject while performing the task.

Internal/External rotation results show consistency between all trials during the swing phase (See Figure 6.7 through Figure 6.12). However, results show inconsistency between all trials during the stance phase. The reason for the inconsistency during stance phase is unclear.

Varus/Valgus rotation showed a trend in the change of rotation – about 17° (See Figure 6.13 through Figure 6.18). All trials showed a valgus (negative on plot) angle of about -7° at heel strike. However, after heel strike, variance between trials was seen (See Figure 6.18).
Figure 6.1: Flexion/Extension as a function of % Gait – Trial 1

Figure 6.2: Flexion/Extension as a function of % Gait – Trial 2
Figure 6.3: Flexion/Extension as a function of % Gait – Trial 3

Figure 6.4: Flexion/Extension as a function of % Gait – Trial 4
Figure 6.5: Flexion/Extension as a function of % Gait – Trial 5

Figure 6.6: Flexion/Extension as a function of % Gait – All Trials
Figure 6.7: Internal/External Rot. as a function of % Gait – Trial 1

Figure 6.8: Internal/External Rot. as a function of % Gait – Trial 2
Figure 6.9: Internal/External Rot. as a function of % Gait – Trial 3

Figure 6.10: Internal/External Rot. as a function of % Gait – Trial 4
Figure 6.11: Internal/External Rot. as a function of % Gait – Trial 5

Figure 6.12: Internal/External Rot. as a function of % Gait – All Trials
Figure 6.13: Varus/Valgus as a function of % Gait – Trial 1

Figure 6.14: Varus/Valgus as a function of % Gait – Trial 2
Figure 6.15: Varus/Valgus as a function of % Gait – Trial 3

Figure 6.16: Varus/Valgus as a function of % Gait – Trial 4
Figure 6.17: Varus/Valgus as a function of % Gait – Trial 5

Figure 6.18: Varus/Valgus as a function of % Gait – All Trials
6.1.2 Internal/External Rotation versus Flexion/Extension

Considerable internal rotation (shown as positive for right knee) occurred throughout the entire gait cycle (See Figure 6.19 through Figure 6.24). After heel strike, the tibia continued to rotate internally. Leading up to toe off, the tibia rotated externally. The period between heel strike and toe off was inconsistent between the five gait trials. Gait trial 3 and 5 did not rotate as far internally compared to the other gait trials. Variance was seen as to when the internal/external rotation in relation to flexion/extension (See Figure 6.24).

Figure 6.19: Flexion/Extension vs Internal/External Rot. – Trial 1
Figure 6.20: Flexion/Extension vs Internal/External Rot. – Trial 2

Figure 6.21: Flexion/Extension vs Internal/External Rot. – Trial 3
Figure 6.22: Flexion/Extension vs Internal/External Rot. – Trial 4

Figure 6.23: Flexion/Extension vs Internal/External Rot. – Trial 5
Data for gait trials commenced about half way through the swing phase and concluded about half way through the next swing phase. The figures show the screws before heel strike in green, screw during stance phase in blue, and screw after toe off in red. The yz plane is a frontal plane, the xy plane is a sagittal plane, and the xz plane is a transverse plane (front view of a right knee).

The axodes for all gait trials were fairly consistent during the swing phases (See Figure 6.25 through Figure 6.37). All trials showed a concentration of tibial rotation at heel strike. Changes in the direction of internal and external rotation were apparent during stance phase. Figure 6.37 shows an axode without an initial swing phase because this trial commenced at heel strike. More kinematic information from the axodes was gleaned through basis/principal screws and invariants. Visible translations were present in all trials, but can be seen in 3, 4, and 5 (Figure 6.31 through Figure 6.37).
Figure 6.25: Gait Trial 1 Axode – Before Heel Strike (Green)

Figure 6.26: Gait Trial 1 Axode – Stance Phase (Blue)
Figure 6.27: Gait Trial 1 Axode – After Toe Off (Red)

Figure 6.28: Gait Trial 2 Axode – Before Heel Strike (Green)
Figure 6.29: Gait Trial 2 Axode – Stance Phase (Blue)

Figure 6.30: Gait Trial 2 Axode – After Toe Off (Red)
Figure 6.31: Gait Trial 3 Axode – Before Heel Strike (Green)

Figure 6.32: Gait Trial 3 Axode – Stance Phase (Blue)
Figure 6.33: Gait Trial 3 Axode – After Toe Off (Red)

Figure 6.34: Gait Trial 4 Axode – Before Heel Strike (Green)
Figure 6.35: Gait Trial 4 Axode – Stance Phase (Blue)

Figure 6.36: Gait Trial 4 Axode – After Toe Off (Red)
6.1.4 Calculated Basis/Principal Screws

The rank of a set of screws is the number of independent screws. All gait trials had a rank of 6. Therefore, 6 independent screws were required to uniquely describe the gait motion. The 6 independent screws (basis screws) for gait trial 1 were obtained by putting the set of screws in row echelon form (See Table 6-1). All other gait trials showed similar results to those shown in Table 6-1. If there are 6 independent screws, then any screw will be a linear combination of the 6 independent screws. Therefore, no defining characteristics were offered by this method. This may have been due to a methodological or physical error and, therefore, more methods were researched and attempted. It is interesting to note the value in row 2, column 3. It is substantially higher than the rest. This might indicate a rotation about the z axis, which corresponds to flexion/extension.
### Table 6-1: Basis Screws for Gait Trial 1

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Among the other methods tried, was the theory of principal screws. When the principal screws were calculated for the gait trials, the principal pitches were not consistent. This means that the system was a higher order system. After further review, it was found that principal screws can only characterize screw systems of order \( \leq 5 \). Other methods of characterizing the screw system were then explored.

#### 6.1.5 Invariants

The pitch of the screw, one the invariants, was plotted against flexion angle. Because pitch is the ratio of angular velocity about the screw axis to translational velocity along the axis, the value of the pitch indicates the contribution levels for each velocity. The larger the pitch value, the more translation dominates the motion. Conversely, the smaller the pitch value, the more rotation dominates the motion. The results show that during the swing phase of gait, nearly all of the motion is due to rotation and that during the stance phase, nearly all of the motion is due to
translation. Both translation and rotation are present during both the stance phase and swing phase, but translation dominates the stance phase and rotation dominates the swing phase (See Figure 6.38 through Figure 6.42). All trials show that translation along the screw dominates when the flexion angle is less than about 20° - 25°.

The moment of the screw is the translational velocity component perpendicular to the screw axis. The moment direction indicates where the next screw in the axode is headed. All trials showed a loop in the lower flexion angles. Assuming that the rotation during the loop is primarily due to internal/external rotation, the perpendicular velocity suggests anterior/posterior drawer and/or medial/lateral translation (See Figure 6.43 through Figure 6.47).

Figure 6.38: Pitch vs Flexion Angle – Gait Trial 1
Figure 6.39: Pitch vs Flexion Angle – Gait Trial 2

Figure 6.40: Pitch vs Flexion Angle – Gait Trial 3
Figure 6.41: Pitch vs Flexion Angle – Gait Trial 4

Figure 6.42: Pitch vs Flexion Angle – Gait Trial 5
Figure 6.43: Screw Moment vs Flexion Angle – Gait Trial 1

Figure 6.44: Screw Moment vs Flexion Angle – Gait Trial 2
Figure 6.45: Screw Moment vs Flexion Angle – Gait Trial 3

Figure 6.46: Screw Moment vs Flexion Angle – Gait Trial 4
6.2 Knee Range of Motion Trials of Experiment One

6.2.1 Internal/External Rotation versus Flexion/Extension

The first ROM trial showed that internal/external rotation nearly followed the same path during flexion as it did during extension (See Figure 6.48). On the other hand, trial 2 was distinct (See Figure 6.49). Murphy hypothesized that co-contraction of the muscles surrounding the knee caused the change in trial 2 [14]. If another trial had been record, perhaps a conclusion could be drawn. Due to the inconsistency of the trials, no conclusions about the mechanism can be made.

Figure 6.47: Screw Moment vs Flexion Angle – Gait Trial 5
Figure 6.48: Internal/External Rot. Vs Flexion/Extension – ROM Trial 1

Figure 6.49: Internal/External Rot. vs Flexion/Extension – ROM Trial 2
6.2.2 Axodes

The yz plane is a frontal plane, the xy plane is a sagittal plane, and the xz plane is a transverse plane (front view of a right knee). The flexion/extension axis was much more pronounced in the ROM trials, which was expected. Trial 1 showed evidence that when the knee flexion turned to extension, there was internal/external rotation (See Figure 6.50 through Figure 6.52). Trial 2 showed nearly no internal/external rotation (See Figure 6.53 through Figure 6.55). Both trials indicated small translations and changes in axis of rotation during the entire ROM.

Figure 6.50: Knee Range of Motion Trial 1 Axode – Full Flexion toward Extension
Figure 6.51: Knee Range of Motion Trial 1 Axode – Transition from Extending to Flexing

Figure 6.52: Knee Range of Motion Trial 1 Axode – Extension to Full Flexion
Figure 6.53: Knee Range of Motion Trial 2 Axode – Full Extension to Extension

Figure 6.54: Knee Range of Motion Trial 2 Axode – Transition from Extending to Flexing
6.2.3 Calculated Basis/Principal Screws

The 6 independent screws (basis screws) for ROM trial 1 were obtained by putting the set of screws in row echelon form (See Table 6-2). All other gait trials showed similar results to those shown in Table 6-2. If there are 6 independent screws, then any screw will be a linear combination of the 6 independent screws. Therefore, no defining characteristics were offered by this method. This may have been due to a methodological or physical error and, therefore, more methods were researched and attempted.

Among the other methods tried, was the theory of principal screws. When the principal screws were calculated for the ROM trials, the principal pitches were not consistent. This means that the system was a higher order system. After further review, it was found that principal screws can only characterize screw systems of order \( \leq 5 \). Other methods of characterizing the screw system were then explored.
### Table 6-2: Basis Screws for ROM Trial 1

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### 6.2.4 Invariants

The pitch remained close to zero for both ROM trials, which was expected (primarily rotation about flexion axis). The extreme flexion/extension angles showed translation. This could be due to contact constraints of the joint. Figure 6.56 in conjunction with Figure 6.57 prove that knee ROM does not behave like a pivot joint.

Assuming that rotation occurred primarily along a combination of the flexion/extension and internal/external rotation axis, Figure 6.58 and Figure 6.59 suggest that anterior/posterior drawer and medial/lateral translation occurred throughout the ROM.
Figure 6.56: Unit Screw Pitch vs. Flexion/Extension Angle – ROM Trial 1

Figure 6.57: Unit Screw Pitch vs. Flexion/Extension Angle – ROM Trial 2
Figure 6.58: Unit Screw Moment vs. Flexion/Extension Angle – ROM Trial 1

Figure 6.59: Unit Screw Moment vs. Flexion/Extension Angle – ROM Trial 2
6.3 Pivot Trials of Experiment One

6.3.1 Internal/External Rotation versus Flexion/Extension

Pivot trials 1 and 2 showed inconsistency in the internal/external rotation versus flexion/extension plots (See Figure 6.60 and Figure 6.61). Trial 1 had double the range of internal/external rotation angle compared to trial 2. However, the range of flexion/extension angles were comparable between the two trials.

Figure 6.60: Internal/External Rot. vs Flexion/Extension Angle – Pivot Trial 1
6.3.2 Axodes

The yz plane is a frontal plane, the xy plane is a sagittal plane, and the xz plane is a transverse plane (front view of a right knee). The axodes shown in Figure 6.62 through Figure 6.64 and Figure 6.65 through Figure 6.68 showed a wide range of rotation and translation and showed domination of internal/external rotation at the beginning. This was expected because of the demands of a pivot step. Neither axode showed resemblance to gait or ROM.
Figure 6.62: Pivot Trial 1 Axode – Primarily External Rotation

Figure 6.63: Pivot Trial 1 Axode – Combination of Rotation/Translation
Figure 6.64: Pivot Trial 1 Axode – Primarily Internal Rotation

Figure 6.65: Pivot Trial 2 Axode – Primarily External Rotation
Figure 6.66: Pivot Trial 2 Axode – Primarily Varus Rotation

Figure 6.67: Pivot Trial 2 Axode – Combination of Rotation/Translation
The 6 independent screws (basis screws) for pivot trial 1 were obtained by putting the set of screws in row echelon form (See Table 6-3). All other gait trials showed similar results to those shown in Table 6-3. It is interesting to note the value found in row 1, column 2. It is significantly higher than the rest. This might indicate rotation about the y axis, which corresponds to internal/external rotation. If there are 6 independent screws, then any screw will be a linear combination of the 6 independent screws. Therefore, no defining characteristics were offered by this method. This may have been due to a methodological or physical error and, therefore, more methods were researched and attempted.
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Among the other methods tried, was the theory of principal screws. When the principal screws were calculated for the pivot trials, the principal pitches were not consistent. This means that the system was a higher order system. After further review, it was found that principal screws can only characterize screw systems of order $\leq 5$. Other methods of characterizing the screw system were then explored.

### 6.3.4 Invariants

The pitch for pivot trials 1 and 2 were erratic (See Figure 6.69 and Figure 6.70). The pitch went from positive to negative several times throughout both trials, indicating that the joint repeatedly switched from pure rotation to a combination of rotation and translation. This is was something that was not anticipated, but interesting information.

Because the axis of rotation was constantly changing, it was hard to glean any valuable information from the moment plots shown in Figure 6.71 and Figure 6.72.
Figure 6.69: Screw Pitch vs Flexion/Extension Angle – Pivot Trial 1

Figure 6.70: Screw Pitch vs Flexion/Extension Angle – Pivot Trial 2
Figure 6.71: Screw Moment vs Flexion/Extension Angle – Pivot Trial 1

Figure 6.72: Screw Moment vs Flexion/Extension Angle – Pivot Trial 2
6.4 Programming

6.4.1 TRACK III

The conversion from FORTRAN (FORTRAN 77, IBM, San Jose, California) to Matlab (R2010a, Mathworks, Natick, Massachusetts) for TRACK III was performed for the plotting routine, which consisted of all subroutines from reading the raw data files to selecting dependent/independent variables to be plotted. Minor changes were made to the manner in which the data was stored. The data was stored linearly in FORTRAN (FORTRAN 77, IBM, San Jose, California), meaning, a block of data was stored in an 1 x n array. For example, if the x value of LED 1 of the second frame was desired, one would call the 225th value (7 variables (x,y,z,a,b,c, & d) multiplied by the number of channels (32)) of the array – i.e. data(225). To simplify the flow of the program and to simplify the condition loops, the arrays were altered in such a way that they were stored in a (number of frames) x (number of LED’s multiplied by number of channels). For example, if the previously mentioned data value were desired, then it now be accessed by frame – i.e. data(2,1). As you can see, this gives a logical break in the data where each row of the array represents a frame in time. All subsequent calls to the data were altered to account for the change in the array structure.

Matlab (R2010a, Mathworks, Natick, Massachusetts) has a versatile, built-in plotting command, therefore this function was utilized in place of the custom coded FORTRAN (FORTRAN 77, IBM, San Jose, California) plotting routine created.

6.4.2 TRACK V

One of the challenges of revitalizing the code for TRACK V was portability – platform to platform differences in data representation. The C code was originally written and compiled on a SPARC machine (Sun Microsystems, Santa Clara, California), which used a Sun Operating
System (SunOS 4, Sun Microsystems, Santa Clara, California) and is a big-endian machine. Endianness refers to the order in which the bytes are stored and read. If a computer is big-endian, it stores and reads the most significant byte first. On the other hand, if a computer is little-endian the opposite is true: it stores and reads the least significant byte first. Therefore, any time binary information was read in from a file, the SPARC (Sun Microsystems, Santa Clara, California) machine would expect the value to be in big-endian form. The binary data files for the aforementioned experiment were created in big-endian format.

The majority of personal computers these days (with the exception of network servers) are little-endian and, therefore, portability is not as big of an issue. However, in order to retrieve the data from the binary files that were created in big-endian format, the program had to be altered to reorder the bytes. Once the bytes were in little-endian format, the data was verifiably correct. It was also proven that the binary files had an inherent offset of one word (two bytes). After this realization and subsequent correction to the program, the data in the binary files was successfully retrieved.

As the TRACK V program progressed, the data were converted from light intensity to \((u,v)\) camera coordinates. After this conversion was complete, the data was sent to a subroutine which corrected camera nonlinearities within the data set. Meaning a calibration table for camera coordinates, \((u,v)\), was created to corrected the error introduced by the curvature of the lens. The program accessed the calibration tables from an external binary file. The calibration routine not only calibrated the \((u,v)\) coordinates of the data, but also scaled it to a usable form for the ensuing subroutine. The calibration tables for TRACK V were not recovered from the data backup tape that was available. Fortunately, several backups were made and those tapes have
been sent out for repair and data retrieval. Therefore, any further processing of Track V data has been put on hold until the calibration tables are retrieved.
Understanding and comparing human knee kinematics is an important aspect of designing and implanting total knee replacements, of knee reconstructive surgery, and of designing long-lasting knee prostheses. In order to successfully compare and contrast knee motion, it must be presented in a way that is independent of coordinate systems and geometry. Several methods of comparing and contrasting knee motion using screws and axodes were explored and tested.

Instantaneous kinematics portray motion so that multiple rotations and translations can be seen on a plot or in one set of data. It is important to understand how knee motion transpires over time. Therefore, instantaneous kinematics are imperative in order to fully comprehend 3D motion.

When screws, axodes, and screw invariants are used in conjunction, a qualitative/quantitative, system independent, method is introduced to compare and contrast knee motion. The geometry of the axode is unique to the generating system and, therefore, can be used for comparison. The screw invariants, screw pitch and screw moment, are also system independent properties that can be used for comparison. When these system independent characteristics are plotted side by side, a greater understanding of human knee motion is obtained.

Ideally, clinicians, surgeons, prosthetists, and designers will use screws, axodes, and screw invariants in an interactive environment to enhance their respective products and services. Understanding and correctly comparing human knee kinematics is key in the development of better products and services.
7.1 Recommendations

Future work should include the comparison of different subjects along with a wider variety of tasks performed. These proposed methods for comparing and contrasting knee motion should be applied to various systems in order to validate its usefulness.
8 BIBLIOGRAPHY


9 VITA

Jacob Hipps is a native of Gilbert, Arizona. He served an LDS mission in Chicago, Illinois, where he learned Spanish. He is a graduate of Brigham Young University. Jacob started his studies at Louisiana State University in August of 2011. He has experience in several different engineering capacities including design, product development, failure analysis, and biomechanics. His technical interests are design, biomechanics, and medical devices.