EVALUATION OF PELVIC OBLIQUITY, TRUNK LEAN, HIP ANGLE, AND HIP ADDUCTION MOMENTS EFFECT ON KNEE ADDUCTION MOMENT IN A YOUNG, HEALTHY POPULATION

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

MASTER OF SCIENCE

IN

KINESIOLOGY AND REHABILITATION SCIENCE

AUGUST 2014

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Keywords: Knee Adduction Moment; Hip Adduction Moment; Pelvic Obliquity; Trunk Lean; Hip Angle
ABSTRACT

**Purpose**  Knee adduction moment (KAM) is recognized as a major contributor to medial knee joint loads with hip adduction moment (HAM) previously linked to KAM in the pathological population. However, HAM is affected by motion at the femur, pelvis, and trunk; therefore, the contributions of frontal plane pelvic obliquity, trunk lean, and hip angle on HAM and KAM were examined. **Methods**  Three-dimensional gait analysis at self-selected walking velocity was performed for nine female and nine male subjects during a single session. A regression analysis model was used to compare contributions of proximal joint motions on HAM and KAM. **Results**  Females walked with higher HAM and KAM compared to males. Individual variables contributing to first peak HAM included trunk lean and pelvic obliquity in females ($R^2=0.55$) and males ($R^2=0.62$). Hip angle and pelvic obliquity in females ($R^2=0.50$) and pelvic obliquity in males ($R^2=0.38$) were related to first peak KAM while HAM alone contributed to 5% and 70% in females and males respectively. Second peak HAM was related to frontal plane hip angle in females ($R^2=0.45$) and pelvic obliquity and trunk lean in males ($R^2=0.35$). Second peak KAM was attributable to trunk lean and hip angle in females ($R^2=0.56$) while only to trunk lean in males ($R^2=0.36$). Hip adduction moment contributed to 34% and 14% of second peak KAM, in females and males respectively. **Conclusion**  The combination of pelvic obliquity, trunk lean, and hip angle, as well as HAM only, explain the substantial variability in KAM during normal walking gait. While previous studies have used only HAM to explain KAM, differences in proximal contributions to both HAM and KAM in the current study suggest this relationship is not as clear as previously thought and proximal variables should be considered individually instead of as a combined hip moment for future research.
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LIST OF ABBREVIATIONS

OA – Osteoarthritis
GRF – Ground Reaction Force
COM – Center Of Mass
KAM – External Knee Adduction Moment
HAM – External Hip Adduction Moment
BMI – Body Mass Index
PO – Pelvic Obliquity
TL – Trunk Lean
HA – Hip Angle
CHAPTER I
INTRODUCTION

The prevalence of joint pathologies in the elderly population has fostered extensive research to identify biomechanical gait characteristics that may lead to the development and progression of these pathologies\textsuperscript{1-9}. Knee osteoarthritis (OA), occurring most commonly in the medial compartment, is the most prevalent of these joint pathologies\textsuperscript{10,11}. Previous research involving this population has been performed in order to better understand the compressive loading during weight-bearing activities leading to the deterioration of the articulating surfaces of the knee\textsuperscript{3,12}. Although a few biomechanical variables have been linked to the progression and severity of knee OA\textsuperscript{1,2,4,5,8,13,14}, little is known about their contribution to the onset of medial knee OA.

External knee adduction moment (KAM) is commonly associated with the progression and severity of OA\textsuperscript{3,6,15}, and it is considered a reliable, indirect method of assessing medial knee compressive forces\textsuperscript{12}. Compared to healthy controls, previous research findings indicate that greater KAM in patients with mild to severe knee OA, with the possible development of a variety of compensatory gait patterns to decrease KAM\textsuperscript{4,8,13,16,17}. Surgical intervention, specifically targeting the reestablishment of neutral alignment of the lower extremity, has previously been reported to provide pain relief and increase function\textsuperscript{18,19}, however, KAM has been reported to return to pre-surgical levels after one year\textsuperscript{20}. These results may indicate that other, possibly more proximal, biomechanical variables are contributing to this increase in KAM.

External hip adduction moment (HAM) has previously been studied as a modifiable factor in reducing KAM in knee OA patients\textsuperscript{1,2,5,7}, with most authors reporting an increased HAM linked to a decreased risk of OA progression\textsuperscript{7}. However, this
relationship has proved difficult to define due to HAM being a net moment encompassing frontal plane motions from the femur, pelvis, and trunk. A compensatory ipsilateral trunk lean has been shown to decrease KAM by shifting the center of mass closer to the stance limb and has been investigated as a gait rehabilitation tool to limit OA progression. However, prolonged trunk lean could lead to a decrease in strength of the hip abductor muscle group, potentially leading to contralateral pelvic drop and the movement of the COM away from the stance limb, typically seen in the Trendelenburg gait. Ipsilateral trunk lean and contralateral pelvic drop create opposing manipulations of the moment arm at the hip and knee, limiting the ability to truly assess the relationship between HAM and KAM.

Gait characteristics in the frontal plane, such as ipsilateral trunk lean, contralateral pelvic drop, and hip angle as they relate and contribute to KAM have yet to be evaluated, although theories about rehabilitation regimens encompassing these variables have been proposed. Evaluating these variables in a young adult, non-pathological population may provide greater insight to their relationship and provide a foundation for the identification of pathological gait patterns. Therefore, the purpose of this study was to examine the influence of frontal plane trunk lean, pelvic obliquity, and hip angle on HAM and KAM during walking gait in a non-pathological, young adult population. We hypothesized that HAM and KAM would present with the same contributing variables. Additionally, we hypothesized that HAM would account for a similar amount of variability in KAM when compared to individual contributing variables.
METHODS

Research Design

A single analysis of biomechanical gait characteristics was conducted to evaluate hip angle, trunk lean, pelvic obliquity, KAM, and HAM in a healthy population. The independent variables were HAM, pelvic obliquity, trunk lean, and hip frontal plane angle. The dependent variables were KAM and HAM.

Participants

Eighteen female (n=9) and male (n=9) non-pathological adults between 20 and 40 years of age from the local community volunteered to participate in this study. Inclusion criteria for all participants consisted of: 1) no previous history of lower extremity fracture, osteotomy, or joint replacement, 2) no lower extremity injury within the last six months, and 3) able to walk continuously for 10 minutes. Prior to the study, all participants signed informed consent forms approved by the Institution’s Committee on Human Studies.

Instruments

Anthropometric data collected were: (1) height, measured with a wall mounted stadiometer (Seca Corp., Hanover, Maryland, USA), (2) weight, measured with a Detecto Certifier scale (Detecto Scale Co., Webb City, Missouri, USA), (3) leg lengths, measured with a measuring tape, and (4) joint widths, measured with a GPM anthropometric caliper (Siber Hegner, Zurich, Switzerland). An adjustable Triton High Low® treatment table (DJO Global, Vista, California, USA) was used for patient and examiner comfort and overall reliability.

Three-dimensional (3D) kinematic data were captured using a 13 camera motion
capture system (Vicon, Inc., Centennial, Colorado, USA) and processed with Vicon Nexus software (Vicon, Inc., Centennial, Colorado, USA). Two AMTI (Advanced Mechanical Technology Incorporated, Boston, Massachusetts, USA) force plates, embedded flush with the floor within the testing field, were used to collect kinetic data. Kinematic data were recorded at 240Hz and time synchronized with kinetic data collected at 960Hz and then smoothed using a Woltering filter (MSE 10). Walking velocity through the four-meter data collection field was measured using two Speedtrap II (Brower Timing Systems, Draper, Utah, USA) infrared sensors. All data were processed using Plug-in Gait (Vicon, Inc., Centennial, CO, USA) and in-house software.

Data Collection Procedures

Data collection sessions were conducted by Board of Certification, certified athletic trainers at the University Human Performance and Gait Laboratory. Anthropometric measurements followed by walking gait assessments were performed during the single data collection sessions.

Twenty-seven reflective markers (18mm in diameter) were attached to the following anatomical landmarks: jugular notch, C7 spinous process, T10 spinous process, inferior angle of the right scapula, sternum at the xiphoid process, and bilaterally at the AC joints, ASIS, PSIS, mid-lateral thighs, lateral and medial knee joints’ axis of rotation, lateral shanks, lateral and medial malleoli, second metatarsal heads, and over the posterior calcanei in accordance with VICON Plug-in-Gait guidelines (Vicon, Inc., Centennial, Colorado, USA).

Participants were asked to walk barefoot across the four-meter data collection field at a self-selected velocity. A successful walking trial included placement of the
entire foot on the force plate without a visible change in gait in an attempt to target the force plate with the appropriate foot. Participants performed the minimum number of trials necessary to obtain three acceptable trials on their dominant leg, defined as which leg they would kick a ball with. Walking velocities were then calculated 25% above and below their self-selected velocity and participants repeated the aforementioned walking trial protocol.

**Statistical Analysis**

Descriptive data statistics of all participants including means, standard deviations (SD), and ranges were generated for all demographic characteristics and variables of interest. Differences in demographics and other variables of interest, such as ground reaction force (GRF), walking velocity, and stride length, between genders were assessed using independent $t$-tests. Data occurring during the first and second peak KAM and HAM variables respectively were used for analysis. Multiple linear regressions, using a step-wise approach, were conducted to predict (1) HAM from pelvic obliquity, trunk lean, and hip angle, (2) KAM from HAM, and (3) KAM from pelvic obliquity, trunk lean, and hip angle. All statistical analyses were conducted using SPSS version 22.0 (IBM, Armonk, NY, USA) with an alpha level of $p<0.05$. All moments were reported as external moments.

**RESULTS**

Demographic data, walking velocity, stride length, and GRF are listed in Table 1. Significant differences between genders were noted for height, weight, walking velocity, second peak GRF, and stride length ($p<0.05$) (Table 1).
Table 1. Demographic and descriptive variables (mean ± standard deviation) for females and males

<table>
<thead>
<tr>
<th></th>
<th>Females (n=9)</th>
<th>Males (n=9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>24.33 ± 2.06</td>
<td>26.00 ± 4.12</td>
</tr>
<tr>
<td>Height (m)*</td>
<td>1.66 ± 0.05</td>
<td>1.76 ± 0.07</td>
</tr>
<tr>
<td>Weight (kg)*</td>
<td>65.05 ± 4.05</td>
<td>81.39 ± 7.84</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>23.75 ± 2.52</td>
<td>26.32 ± 1.88</td>
</tr>
<tr>
<td>Walking Velocity (m/s)*</td>
<td>1.37 ± 0.32</td>
<td>1.23 ± 0.27</td>
</tr>
<tr>
<td>Stride Length (m)*</td>
<td>1.36 ± 0.11</td>
<td>1.29 ± 0.10</td>
</tr>
<tr>
<td>GRF-P1 (Nm/kg)</td>
<td>10.24 ± 0.90</td>
<td>9.51 ± 1.97</td>
</tr>
<tr>
<td>GRF-P2 (Nm/kg)*</td>
<td>10.50 ± 0.72</td>
<td>9.58 ± 1.82</td>
</tr>
</tbody>
</table>

n=Sample Size; yrs=Years; m=Meters; kg=Kilograms; BMI=Body Mass Index; kg/m²=Kilogram per Squared Meters; m/s=Meters per Second; GRF-P1=First Peak Ground Reaction Force; GRF-P2=Second Peak Ground Reaction Force; Nm/kg=Newton Meters per Kilogram

*=Significant differences between females and males (p<0.05)

Descriptive statistics for first peak HAM in females and males are presented in Table 2. The following gender specific regression equations for the prediction of first peak HAM from pelvic obliquity (PO), trunk lean (TL), and hip angle (HA) were identified as the most parsimonious models:

Females: HAM = (0.038*TL) + (0.041*PO) + 0.73 (R²=0.55)
Males: HAM = (0.084*PO) + (0.054*TL) + 0.655 (R²=0.62)

Table 2. Pelvic obliquity, trunk lean, and hip angle during first peak HAM for females and males (mean ± standard deviation)

<table>
<thead>
<tr>
<th></th>
<th>Females (n=9)</th>
<th>Males (n=9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAM (Nm/kg)</td>
<td>0.91 ± 0.16</td>
<td>0.73 ± 0.21</td>
</tr>
<tr>
<td>Pelvic Obliquitya (°)</td>
<td>5.03 ± 1.67</td>
<td>2.72 ± 1.30</td>
</tr>
<tr>
<td>Trunk Leanb (°)</td>
<td>-0.59 ± 2.04</td>
<td>-2.87 ± 1.82</td>
</tr>
<tr>
<td>Hip Anglec (°)</td>
<td>6.61 ± 4.08</td>
<td>2.65 ± 3.20</td>
</tr>
</tbody>
</table>

HAM=Hip Adduction Moment; n=Sample Size; Nm/kg=Newton Meters per Kilogram; °=Angular Degrees
aPelvic Obliquity (+contralateral pelvic rise/-contralateral pelvic drop)
bTrunk lean (+ipsilateral trunk lean/-contralateral trunk lean)
cHip Angle (+adduction/-abduction)
Descriptive statistics for second peak HAM in females and males are presented in Table 3. The following gender specific regression equations for the prediction of second peak HAM from pelvic obliquity, trunk lean, and hip angle were identified as the most parsimonious models:

Females: \( \text{HAM} = (0.025 \times \text{HA}) + 0.78 \) \( R^2 = 0.45 \)

Males: \( \text{HAM} = (0.073 \times \text{PO}) + (0.047 \times \text{TL}) + 0.775 \) \( R^2 = 0.35 \)

Table 3. Pelvic obliquity, trunk lean, and hip angle during second peak HAM for females and males (mean ± standard deviation)

<table>
<thead>
<tr>
<th></th>
<th>Females (n=9)</th>
<th>Males (n=9)</th>
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<tbody>
<tr>
<td>HAM (Nm/kg)</td>
<td>0.78 ± 0.16</td>
<td>0.66 ± 0.19</td>
</tr>
<tr>
<td>Pelvic Obliquity(^a) (°)</td>
<td>-1.91 ± 1.93</td>
<td>-0.58 ± 1.10</td>
</tr>
<tr>
<td>Trunk Lean(^b) (°)</td>
<td>0.59 ± 1.93</td>
<td>-1.49 ± 1.61</td>
</tr>
<tr>
<td>Hip Angle(^c) (°)</td>
<td>-0.12 ± 4.23</td>
<td>1.13 ± 3.16</td>
</tr>
</tbody>
</table>

\( \text{HAM} = \) Hip Adduction Moment; \( n = \) Sample Size; \( \text{Nm/kg} = \) Newton Meters per Kilogram; \( ° = \) Angular Degrees

\(^a\)Pelvic Obliquity (+contralateral pelvic rise/-contralateral pelvic drop)

\(^b\)Trunk lean (+ipsilateral trunk lean/-contralateral trunk lean)

\(^c\)Hip Angle (+adduction/-abduction)

Descriptive statistics for first peak KAM in females and males are presented in Table 3. The following gender specific regression equations for the prediction of first peak KAM from HAM were identified as the most parsimonious models:

Females: \( \text{KAM} = (-0.161 \times \text{HAM}) + 0.85 \) \( R^2 = 0.05 \)

Males: \( \text{KAM} = (0.737 \times \text{HAM}) + 0.086 \) \( R^2 = 0.70 \)

The following gender specific regression equations for the prediction of first peak KAM from pelvic obliquity, trunk lean, and hip angle were identified as the most parsimonious models:
Females: \[ KAM = (-0.028*HA) + (0.033*PO) + 0.714 \quad (R^2 = 0.50) \]

Males: \[ KAM = (0.086*PO) + 0.366 \quad (R^2 = 0.38) \]

Table 4. HAM, pelvic obliquity, trunk lean, and hip angle during first peak KAM for females and males (mean ± standard deviation)

<table>
<thead>
<tr>
<th></th>
<th>Females (n=9)</th>
<th>Males (n=9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAM (Nm/kg)</td>
<td>0.70 ± 0.11</td>
<td>0.61 ± 0.18</td>
</tr>
<tr>
<td>HAM (Nm/kg)</td>
<td>0.88 ± 0.16</td>
<td>0.72 ± 0.20</td>
</tr>
<tr>
<td>Pelvic Obliquity(^a) (°)</td>
<td>5.43 ± 1.65</td>
<td>2.89 ± 1.28</td>
</tr>
<tr>
<td>Trunk Lean(^b) (°)</td>
<td>-0.69 ± 2.07</td>
<td>-2.90 ± 1.08</td>
</tr>
<tr>
<td>Hip Angle(^c) (°)</td>
<td>6.84 ± 4.16</td>
<td>5.36 ± 2.09</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Females (n=9)</th>
<th>Males (n=9)</th>
</tr>
</thead>
</table>
| HAM=Hip Adduction Moment; KAM=Knee Adduction Moment; n=Sample Size; Nm/kg=Newton Meters per Kilogram; \(^a\)=Angular Degrees
| \(^a\)Pelvic Obliquity (+contralateral pelvic rise/-contralateral pelvic drop)\n| \(^b\)Trunk lean (+ipsilateral trunk lean/-contralateral trunk lean)\n| \(^c\)Hip Angle (+adduction/-abduction)\n
Descriptive statistics for second peak KAM in females and males are presented in Table 5. The following gender specific regression equations for the prediction of second peak KAM from HAM were identified as the most parsimonious models:

Females: \[ KAM = (-0.252*HAM) + 0.626 \quad (R^2 = 0.34) \]

Males: \[ KAM = (0.212*HAM) + 0.257 \quad (R^2 = 0.14) \]

The following gender specific regression equations for the prediction of second peak KAM from pelvic obliquity, trunk lean, and hip angle were identified as the most parsimonious models:

Females: \[ KAM = (-0.010*HA) + (-0.018*TL) + 0.447 \quad (R^2 = 0.60) \]

Males: \[ KAM = (0.047*TL) + 0.445 \quad (R^2 = 0.36) \]

Table 5. HAM, pelvic obliquity, trunk lean, and hip angle during second peak KAM for females and males (mean ± standard deviation)
<table>
<thead>
<tr>
<th>Measurements</th>
<th>Females</th>
<th>Males</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAM (Nm/kg)</td>
<td>0.44 ± 0.09</td>
<td>0.39 ± 0.12</td>
</tr>
<tr>
<td>HAM (Nm/kg)</td>
<td>0.74 ± 0.20</td>
<td>0.62 ± 0.21</td>
</tr>
<tr>
<td>Pelvic Obliquity (°)</td>
<td>-2.12 ± 2.10</td>
<td>-0.67 ± 1.24</td>
</tr>
<tr>
<td>Trunk Lean (°)</td>
<td>0.68 ± 1.82</td>
<td>-1.20 ± 1.50</td>
</tr>
<tr>
<td>Hip Angle (°)</td>
<td>-0.68 ± 4.35</td>
<td>3.78 ± 2.77</td>
</tr>
</tbody>
</table>

HAM=Hip Adduction Moment; KAM=Knee Adduction Moment; n=Sample Size; Nm/kg=Newton Meters per Kilogram; °=Angular Degrees

aPelvic Obliquity (+contralateral pelvic rise/-contralateral pelvic drop)
bTrunk lean (+ipsilateral trunk lean/-contralateral trunk lean)
cHip Angle (+adduction/-abduction)

DISCUSSION

Previous authors have assessed the relationship of proximal trunk and pelvic motions with frontal plane knee mechanics, but have done so in an older and pathological subjects or in an attempt to determine the appropriate goals for rehabilitation programs\(^4,8,13,17\). However, it is difficult to determine the appropriate relationship amongst these variables in the pathological population, as age and compensatory motions may affect the results. In the present study, non-pathological adults’ patterns of movement of proximal body segments, specifically the trunk and pelvis, significantly contributed to the first and second peaks of HAM and KAM during normal walking gait. However, contributions from these variables were different for HAM and KAM, as well as, between genders.

The variability within HAM consisted of 55% and 62% for by pelvic and thorax motion in females and males, respectively. Females presented with greater pelvic motion and less trunk motion when compared to males. Previous research findings relative to proximal contributors to KAM indicate that OA subjects appeared to control the movement of their COM with their trunk and pelvis individually, whereas, healthy control subjects balance motion between their trunk and pelvis\(^4\). The results of the
current study suggests that the females more closely resemble the OA patients by shifting their COM over their stance limb by raising their pelvis while the males more closely resemble control subjects by balancing motions between the trunk and pelvis. This idea is further supported by the observation that females demonstrated greater first peak HAM when compared to males, similar to the relationship between OA patients and controls.

The association of HAM and KAM has been examined within the OA population, however, due to the contribution of the pelvis and trunk on HAM, it is difficult to interpret this association and target specific body segments to manipulate KAM. In the current study, first peak HAM accounted for 70% and 5% of the variability in KAM for males and females, respectively. Individual variable analysis reported significant contribution of pelvic obliquity to KAM in males, accounting for 38% of the variability. Hip angle and pelvic obliquity were significant contributors to KAM in females, accounting for 50% of the variability. Our results revealed differences between individual variable contributors to HAM, contributions of HAM and individual variables to KAM, and variable contributions between genders. This complex association amongst proximal variables indicates inconsistency in previous literature findings\textsuperscript{1,2,4,5,7,8,13,17} and that using only HAM to evaluate KAM is not ideal.

Limited research has been conducted to evaluate the effect of high second peak HAM, with conflicting reports as to its effect within the moderate to severe OA populations\textsuperscript{4,5,14}. In the current study, second peak HAM in males was attributable to trunk lean and pelvic obliquity, similar to that in the first peak, however, these accounted for only 35% of the variability compared to 62% of the variability accounted for in the first peak. In females, only hip angle was reported as a significant contributor for second
peak HAM, accounting for 45% of the variability, compared to pelvic obliquity and trunk lean in first peak. Pelvic obliquity and trunk lean contributed to the variability in second peak HAM in the male participants, indicating more proximal control of the COM. In females, hip angle was the only contributing variable to second peak HAM, with dramatic changes in frontal plane hip angle between first and second peaks (6.61° to 0.12°, respectively), indicating increased frontal plane hip joint motion throughout stance.

Increases in second peak KAM are not commonly associated with the progression of OA, as distal compensatory motions have been reported to decrease second peak KAM in patients with less severe OA. In the current study, both females and males had decreased second peak KAM values when compared to first peak. Second peak HAM accounted for 34% and 14% of the variability in KAM for females and males, respectively. Individual contributions accounted for much more than HAM alone, with hip angle and trunk lean accounting for 60% of the variability in females and trunk lean alone accounting for 36% of the variability of KAM in males. Only one previous study has found significant contribution from proximal variables, reporting 7% of the variability in KAM attributed to trunk lean. However, the combination of data from both genders in this previous study may not be an appropriate representation of the variability within KAM, as the results from the current study revealed different contributing variables for each gender. No research, to our knowledge, has been conducted on second peak HAM contributions to second peak KAM, although, the current results suggest the variability within HAM could allow for limited influence
compared to the contributions from individual variables when evaluating second peak KAM.

Previous findings identified other contributing variables, such as toe-out gait and mechanical axis angles to explain HAM$^{2,8}$ and KAM$^{2,8,12}$. These variables were not included into the regression analysis as the current study’s objective was to investigate proximal biomechanical variables. However, due to their stated contribution, variables found to be significantly different between genders will be discussed. The current study revealed higher walking velocity in females than in males, leading to increased stride length (Table 1). Although previous results have reported self-selected walking velocity to contribute as much as 10% to first peak HAM$^2$ and as much as 8.9% in peak KAM$^{16}$ in OA and control subjects, Huang et al. (2008) suggested that velocity did not contribute to the altered mechanics of the lower limb in the frontal plane but that instead, compensatory gait strategies were adopted in the frontal plane to maintain the gait velocity in OA subjects$^{14}$. Ground reaction force is commonly reported as a main contributor to lower extremity moments and was significantly different during second peak HAM and KAM between genders in the current study (p=0.02) (Table 1). Although males had lower GRF along with lower HAM and KAM compared to females, previous research suggests greater contributions to KAM from the moment arm rather than GRF$^9$. The current results may support this conclusion, as hip angle was considered a significant contributor to first and second peak KAM in females only. The more abducted femur in females could potentially create a more varus knee angle, allowing for an increased moment arm and frontal plane moments about the knee when compared to males.
The results of the current study reveal high variability amongst proximal biomechanical variables that have been previously proposed to contribute to KAM. Based on differences between genders, contributions of individual variables to HAM and KAM reveal males and females may manipulate frontal plane knee joint loading in different ways. In most cases, the combination of individual variables accounted for greater variability within KAM than using HAM alone, possibly indicating HAM is too complex and draws from too many variables to be a valuable resource when assessing proximal contributions to KAM. Therefore, influences of pelvic obliquity, trunk lean, and frontal plane hip angle may provide greater insight into changes KAM and help isolate compensatory motions.

Clinical Application

The ability to identify compensatory motions in gait is important for physical rehabilitation specialists to understand individuals’ responses to pathology. Individuals with knee OA use these compensatory gait patterns to manipulate COM over the stance limb\(^1,4,5\). Knowledge of the contributions these variables have on KAM on healthy and pathological individuals may further help to identify individuals at risk of developing knee OA. Ipsilateral trunk lean or contralateral pelvic hike may also help to prevent progression of the pathology if utilized properly to develop gait-retraining protocols when treating knee OA. These simple modifications to gait could manipulate the COM over the stance limb, leading to a decrease in moments around the knee joint\(^13,17\). Prolonged gait compensations, however, potentially may lead to weaknesses in muscles or pathology in other joints, which should be considered when treating patients to avoid further complications\(^21-23\).
Conclusion

Contrary to previous research that has used HAM only to describe changes in KAM, the current study revealed differences in proximal contributions to both HAM and KAM, as well as between genders. Understanding KAM and its proximal contributions in a young population may provide more insight to the deviation of these variables in pathological gaits. However, comparison between the young, healthy subjects in the current study and previous research including OA patients should be approached with caution, as it is unclear how gait changes over time due to age or the early development of compensatory gait patterns due to OA.
CHAPTER II
REVIEW OF LITERATURE

Epidemiology of OA

Knee osteoarthritis (OA) is a prevalent joint disorder affecting an increasing amount of people. As the population ages, more individuals develop knee OA, however, exact prevalence is unknown due to vast differences in epidemiologic study designs. In a cross-sectional health examination survey conducted in 1988-1994, the Third National Health and Nutritional Examination Survey (NHANES III) sampled adults age ≥60 across the United States using a multistage, stratified probability cluster randomizing process. Household interviewers collected surveys regarding demographic and symptom data. Physical performance examinations and knee radiographs were performed in Mobile Examination Centers by health technicians. Interviewers collected demographic and symptomatic data self-reported by participants. Single non-weight-bearing radiographs were scored with the Kellgren Lawrence (K/L) grading system by a radiologist with 10% of the radiographs confirmed by a second radiologist. Multivariable adjusted odds ratios were used for dependent variables. Trend tests were used to assess differences amongst demographics and t-tests were used for group differences. Significantly more women had a severe knee OA radiograph (K/L grade >2) than men (12.9% vs. 6.5%) with overall 37.4% of the participants having K/L grades ≥2 in at least one knee. Amongst individuals with grade ≥2 radiographs, 12.1% had symptomatic knee OA. Factors that were most strongly associated with greater prevalence of symptomatic or radiographic knee OA included increased age, female gender, increased BMI, and non-Hispanic Black race/ethnicity. Individuals with symptomatic knee OA self-reported activity limitations and poorer physical performance tasks. Participants with both
symptomatic and radiographic knee OA had significantly greater overall analgesic use as well.\textsuperscript{10}

Further epidemiologic data was done by Zhang et al. (2001) investigating the prevalence of knee OA in an elderly Chinese population in comparison to the prevalence of knee OA in a Caucasian population as seen in the Framingham Study. Methodology being the most determinant factor for an epidemiologic study’s validity, Zhang et al. (2001) used the methods of the Framingham Study and applied it to a population within Beijing, China. Participants were randomly recruited via door-to-door home interviewing process within predetermined randomized district sections. Questionnaires focused on knee joint symptoms, previous diagnosis of arthritis, and possible risk factors for OA, similar to questionnaires involved in the Framingham Study. Amongst the 1,953 participants who completed the home interview, 1,787 participated in subsequent clinical examination and weight-bearing anteroposterior knee radiographs as was done in the Framingham Study. One radiologist read the radiographs after corroborating with results from the Framingham Study. Using the K/L grading scale, interreader reliability and intrareader reliability was 0.83 and 0.79 respectively with disagreements not occurring in any particular direction decreasing the likelihood of bias in estimates. Subjects were divided into five age groups: 60-64, 65-69, 70-74, 75-79, and ≥80. Age specific prevalence of radiographic and symptomatic knee OA were calculated separately by gender as applied in the Framingham Study. On average, elderly Chinese subjects in Beijing had lower body mass index (BMI) (mean BMI 25-26 kg/m\textsuperscript{2}). Radiographic and symptomatic knee OA increased with age and was more common in women within the elderly Chinese population. Prevalence of radiographic knee OA in Chinese men was
lower than Caucasian men under the age of 70, similar between 70 and 79 years, and slightly higher in ages greater than 80. Symptomatic knee OA among Chinese men appeared slightly higher than Caucasian men except for below 70 years old. Chinese men also seemed less likely to have unilateral or severe radiographic knee OA compared with Caucasian men. Chinese women had a higher prevalence of both radiographic and symptomatic knee OA than Caucasian women, 45% and 43% respectively. There was no significance found with prevalence of severe radiographic knee OA between the two groups but Chinese women had a higher prevalence of bilateral radiographic knee OA. Compared to their age-matched Caucasian counterparts, elderly Chinese women had a substantially higher prevalence of both radiographic and symptomatic knee OA while the men were roughly similar. Zhang et al. (2001) makes inferences to the lower BMI of the Chinese population having a similar or a higher prevalence of knee OA than the Caucasian population attributing development of the disease to a higher physically active lifestyle although unknown if its true. These results suggest knee OA affects a large amount of the population, both in the United States and in China.\textsuperscript{11}

\textit{Total Knee Arthroplasty}

As prevalence of knee OA rises, increasing need of treatment becomes a greater burden on health care. When knee OA becomes more severe and symptoms become intolerable, TKA becomes an option that can alleviate the pain and increase function. Total knee arthroplasty (TKA) replaces damaged tibial and femoral surfaces with artificial implants\textsuperscript{20}. After TKA, pain and satisfaction becomes a main outcome for patients who undergo the expensive procedure\textsuperscript{18}. Baker et al. (2007) investigated satisfaction levels of TKA patients in relation to pain and function approximately one
year post-operation. Questionnaires containing the Oxford knee score and additional questions relating to knee problems and satisfaction of surgery outcome were sent to 10000 unilateral TKA patients randomly selected from the National Joint Registry for England and Wales. The Oxford knee score questionnaire involved 12 questions, formatted as a 1-5 likert scale (minimum score of 12 and maximum score of 60 with lower scores indicating lower pain or higher function and higher scores indicating higher pain and lower function), relating to a subjective assessment of pain and function. Pain scores and function scores were evaluated separately and standardized to be comparable. Multivariable logistic regression was performed to investigate which factors influenced patient satisfaction. Of the 8231 questionnaires returned, 8095 completed the satisfaction question in which 81.8% were satisfied of their outcome, 11.2% were unsure, and 7.0% were not satisfied. The mean of the Oxford knee score in patients who were satisfied was 22.0 while those who were unsure and not satisfied with their outcome was 35.2 and 41.7 respectively. Significant differences were also seen in the pain and function scores with the mean standardized pain and function scores were 0.19 (0to 1) and 0.22 in the satisfied patients, 0.63 and 0.61 in the unsatisfied patients, and 0.48 and 0.49 in the unsure patients respectively. Pain and function were also strongly correlated (Pearson’s correlation coefficient (r)=0.83). Results of this study ensure TKA as a successful intervention for severe knee OA.

Knee Adduction Moment

The medial knee compartment is known to be a common site for progression of OA within the knee\(^3\).\(^{12}\). A potential cause of the progression is an increased load through the compartment during gait. Knee adduction moment (KAM) is the product of the
vertical ground reaction force (GRF) and the moment arm extending from the knee joint center. Zhao et al. (2007) used an in vivo approach to investigate the impact various gait patterns and its associated knee adduction torque has on medial contact force. A single 80-year-old male with an instrumented right knee implant able to measure force distribution was recruited to collect kinematic and kinetic gait data. Five gait patterns to appreciate an influence of changes in KAM (normal, fast, slow, wide stance, and toe-out) were observed at self-selected walking speed. Relationship of medial contact force within the knee collected from the implant and knee adduction torque collected during over-ground gait was analyzed using correlation analyses. Each analysis was performed within each gait pattern and amongst all gait patterns together. \( R^2 \) values were calculated for the entire gait cycle and only the stance phase. The largest peak axial force was 2.74 times of body weight (BW) with a corresponding medial force of 1.73 BW, which occurred during a fast gait trial, while the smallest occurred during a slow gait trial producing a 2.06 BW axial force and a corresponding 1.28 BW medial force. The shape of the medial contact force curve closely followed the shape of the total contact force curve however the shape of each KAM curve did not necessarily follow the corresponding medial force curve shape nor did the peaks necessarily match. The largest KAM peak was 3.37% BWxheight (HT) occurring during a toe-out gait and the smallest peak was 2.13% BWxHT occurring during a fast gait trial. Significant correlations were found between KAM and both the medial contact force and the medial to total contact force ratio (p<0.001). Medial to total contact force ratio produced \( R^2 \) values between 0.54 and 0.90 for individual trials and 0.69 for all trials together. Based on their one patient study, Zhao et al. (2007) believe the large \( R^2 \) support their hypothesis that KAM is
a good external measure of internal medial contact force and medial to total contact force ratio during gait.\textsuperscript{12}

Knee adduction moment during gait involves the contribution of the ground reaction force (GRF) and the perpendicular distance from the GRF to the knee joint center, commonly called the lever or moment arm\textsuperscript{9}. Hunt et al. (2006) examined the relationship amongst these variables. One hundred knee OA patients underwent gait analysis at self-selected velocity. Paired $t$-tests were used to compare KAM, GRF, and lever arm between limbs and a two-factor repeated measures analysis of variance (ANOVA) was used to evaluate differences between variables in the time to peak magnitude. Tukey HSD post hoc analysis was used for significant main effects. Pearson’s product moment correlation coefficients and Fisher’s Z transformation were also used. The frontal plane lever arm during gait was typically positioned lateral to the knee joint center in early stance and moved medially by 10\% of stance in the participants. Peak KAM and peak lever arm magnitudes were significantly greater in affected limbs compared to the unaffected side while peak frontal plane GRF were significantly less in the affected limbs. At midstance, lever arm and KAM were greater in the affected limb. Peak magnitudes for each variable were found to occur at significantly different times of the gait cycle. Peak KAM in both limbs were positively correlated for peak GRF and peak lever arm. Significant correlation between peak GRF and peak lever arm only existed in the unaffected limb and only when normalized to body size. Peak lever arm magnitudes were greater in knees with OA and were more highly correlated with KAM than GRF with KAM. Lever arm did not exhibit the same double hump pattern as KAM and GRF and changed little throughout stance. As peak frontal plane GRF was less in the
affected knees, KAM was still greater suggesting it was mainly the result of the lever arm. These results suggest that if peak KAM doesn’t coincide with the peak in dynamic lower limb alignment, as measured with the lever arm during gait, it may be unreasonable to presume that KAM coincides with a static measure of lower limb alignment.\(^9\)

Moyer et al. (2010) investigated the interaction body mass and knee alignment had on knee joint loading in 487 knee OA patients. Participants underwent 3D gait analysis at their typical walking speed to obtain kinematic and kinetic data and standing anteroposterior radiographs of their lower limb to obtain their knee alignment. Sequential (hierarchical) linear regression models were used to test the interaction between alignment and body mass on KAM. Participants were also divided into subgroups based on tertiles of knee alignment and body mass. Associations between alignment and KAM during walking were observed to be dependent on body mass with higher mass having a greater impact. The highest tertile for mass suggested a 3.2Nm increase in KAM for every 1° increase of varus alignment. Mechanical axis angle of the knee was also found to be influential on KAM even in the lowest tertile of mass, with results suggesting a 1.7Nm increase of peak KAM for every 1° of increased varus. Results also suggest an increase of 0.4Nm KAM for every 1kg increase of mass. Based on their findings, Moyer et al. (2010) supports rational for decreasing body mass and altering knee alignment in patients with knee OA as interventions.\(^{15}\)

Dynamic knee alignment, specifically more varus knee alignment, during gait appears to affect levels of KAM in previous studies\(^9,15\), potentially influencing GRF and the moment arm at the knee\(^9\). Knee adduction moment at controlled walking velocities has been related to OA progression\(^3\). Uncertainties of whether walking velocity is a
result of OA patients trying to reduce KAM or slower velocities result from aging and pain lead Mundermann et al. (2004) to investigate the effect walking velocity has on KAM in 44 knee OA patients and 44 matched controls. Gait analysis was performed at a comfortable self-selected walking velocity for all participants. Linear regression analysis was used to relate KAM and walking velocity and t-tests were used to compare those results between OA severities as well as control walking velocities. Bonferroni corrections were used for significant results. Differences in KAM among the participants were evaluated using repeated measures ANOVAs. Walking velocity only explained 8.9% of the variance in KAM between OA patients while no significant relation was found for the control group. Walking velocities were not significantly different between the OA group and control group, however, KAM was significantly higher in severe OA subjects compared to control and less severe OA subjects. Based on these results, Mundermann et al. (2004) suggests that the relationship between KAM and self-selected walking velocity is weak and highly patient specific with only a few individuals using slower walking velocities to reduce KAM. Mundermann et al. (2004) also suggests that KAM may not initially cause OA, but rather, effect the mechanical axis angle of the pathological joint further progressing OA.16

Although KAM is known to be a biomechanical factor of knee OA3,6,15, little is known about its relationship longitudinally. Miyazaki et al. (2002) observed the progression of medial knee OA and the corresponding knee adduction moment in a sample of 106 patients with knee joint OA. All patients had a varus alignment in one or two knees and which were considered to contain medial compartment knee OA. Prior to gait analyses, radiographic evaluations, and pain assessments, each subject underwent a
A four-week period of anti-inflammatory drugs and physiotherapy. All radiographs were taken initially and at the six-year follow up in the same manner. A single blinded experimenter evaluated and graded each radiograph based on osteophyte formation and joint space narrowing. Natural walking speed for kinematic and kinetic data were collected. Knee pain was evaluated using the Hospital for Special Surgery pain subscale. Knees with and without disease progression were compared using the chi-square test for discrete variables and the t-test was used to test for equality of the continuous variables. Relationships between adduction moments and other variables at entry were tested using simple and multiple regression analyses, as was joint space loss and baseline variables. Radiographic disease progression was examined using a logistic regression model. Disease progression was observed in 32 of the 74 patients that completed the study. There were 15 patients who underwent TKA and did not finish the study, but these patients tended to be older, had more varus alignment, less joint space width, more pain, and higher KAM than other participants at entry of the study. Knee pain and KAM at baseline was significantly higher in the group with radiographic progression. There were also significant correlations between amount of joint space width loss at six years and baseline pain score, mechanical axis, adduction moment, and joint space width. Knee adduction moment was positively correlated with pain score, mechanical axis, and negatively with joint space width, after adjusting for age and pain. After logistic regression analysis with radiographic disease progression as the dependent variable, KAM and age were significant independent variables. The risk of progression increased 6.46 times with a 1% increase in KAM and 1.22 times with a one-year increase in age. The predictive value of the adduction moment for radiographic disease progression was
80% using a cut off value of 5% BWxHT suggesting KAM may be a valuable predictor of medial compartment knee OA progression. During entry, patients who had more pain had higher KAM and patients with less pain had lower KAM. Results of Miyazaki et al. (2002) suggest knee adduction moment appears to be a major variable when predicting medial compartment knee OA progression.³

Corrective operations for knee OA typically involve knee angle realignment to reduce the varus deformity consequence of OA progression⁶. Prodromos et al. (1985) studied 21 patients with high tibial osteotomy (HTO) prior to, one year, and about 3.2 years after operation. Walking kinematic and kinetic data were collected at fast, normal, and slow speeds pre-HTO and one-year after. Clinical evaluation at pre, one-year, and average 3.2 years post-HTO involved a modified Hospital for Special Surgery 100-point rating scale for pain, function, and deformity. Standing radiographs were used to assess for alignment and indications of arthritis pre-HTO and follow-up examinations. Student tests were used to find differences among group averages. Tests of significance of Pearson correlation coefficients were evaluated using the t statistic. Fisher’s exact test was also used when appropriate. Patients were divided into a high and low group based on peak KAM magnitude with a grouping cutoff of 4.0% BWxHT moment (one SD above the mean) and statistically similar pre-HTO average varus deformities and mean clinical scores. There were no significant correlations between alignment angle and peak KAM although patients’ averages were higher than controls’. Alignment was associated with a reduction in peak KAM in patients at one-year post-HTO with an average change of 9° of varus to 1.8° of valgus alignment immediately after HTO. Peak KAM at one-year post-HTO reduced in both groups with the high group reduced to statistically normal
levels and the low group reduced to statistically lower than normal levels. The peak abduction moment at the knee was significantly lower than normal in the high group while no difference was found in the low group. No difference, compared to controls, in stride length was found in the high group, but stride length was significantly below normal in the low group. The low group had significantly better clinical results at an average of 3.2 years compared to the high group with all five HTO failures occurring in the high group. Alignment in the high group changed from an average of 2° valgus to 3.6° varus at the last follow-up while the low group had not differed from immediately after HTO. Pre-HTO KAM was positively correlated with varus alignment at the last follow-up. Although TKA was not involved with Prodomos et al. (1985), HTO involves corrective alignment in patients with OA. It is suggested through their results that pre-HTO peak KAM is predictive of clinical results at an average of 3.2 years post-HTO with lower KAM producing better results. In spite of varus deformity, some patients experienced lower than normal peak adduction moments. The lower group continued to have lower post-HTO KAM than the higher group even though both had corrective realignments indicating dynamic compensations may continue to occur despite mechanical changes. Return of varus alignment in the high KAM group also suggests a dynamic compensation may still be present continually permitting medial knee load.  

*Knee Adduction Moment Post Total Knee Arthroplasty*

Total knee arthroplasty is becoming an increasingly common treatment of end-stage knee OA. Similarly to HTO, TKA involves realignment of varus deformity and removing damaged bone surface. Knee adduction moment has been acknowledged as being a biomechanical contributor to OA progression, but there is little literature
relating KAM, alignment, and the affects of TKA. Hatfield et al. (2011) investigated the
kinematics and kinetics of sixty patients with severe knee OA electing to undergo TKA
through gait analysis one-week prior and approximately one year after operation. Gait
analysis was done at self-selected walking speed. Principal component analysis was
performed to analyze waveform patterns for external knee joint moments. Means and
standard deviations (SD) were calculated for demographic characteristics and for the
principle component scores for knee flexion angle, flexion moment, adduction moment,
and rotation moment. The Western Ontario and McMasters Universities Osteoarthritis
Index (WOMAC) scores, walking speed, and stride length significantly improved one
year post-TKA. According to the principal component analysis, post-TKA KAM was
significantly lower than pre-TKA during most of stance phase. Post-TKA, patients had a
greater difference between the first peak of KAM in early stance and midstance KAM
compared to pre-TKA. Hip-knee-ankle angles were measured using standard
radiographs. Regression analysis showed that post-TKA reduction of angle explained
30% of the variance in the change of KAM during stance phase and 0.3% of the variance
of early and midstance peak KAM, which was not significant. Knee flexion moments
post-TKA followed a more typical bimodal pattern during stance. Post-TKA, patients
had less of an early stance phase external rotation moment than pre-TKA. Patients’ post-
TKA showed improvements in outcome measures and walking velocity. Based on the
entire principal component analysis waveforms, patients’ dynamic loading environment
and knee motion improves one-year post TKA with exception of external rotation
moment. A reduction in post-TKA KAM and a decrease in midstance values supported
previous literature and implies a decrease in medial compartment loading during gait, even though walking velocity increased.¹⁹

Although Hatfield et al. (2011) had a significant relationship between TKA and KAM¹⁹, the pattern of KAM is still unknown between pre-TKA and the one-year post-TKA mark. Orishimo et al. (2012) investigated the kinematics and kinetics in the frontal plane of 15 TKA patients pre-operation, six months, and one year post-operation. Kinematic data were taken with five infrared cameras (60 Hz) and forceplates (960 Hz) flush to the ground. Patients performed five walking trials at self-selected velocities. Separate repeated measures ANOVAs were used for (time x phase) to compare changes in peak KAM and knee adduction impulse for breaking and propulsive phases with respect to time period. Post hoc paired t-test with Bonferroni corrections were used when significant effects were found to compare knee alignment, knee score, or biomechanical variables with respect to time period. Associations between knee adduction moment and impulse, gait velocity, static alignment, and peak varus angle during gait were investigated using Pearson correlations at each collection period. Peak knee adduction angle during gait initially was reduced to 37% of pre-operative levels at six months but increased to 53% of preoperative levels at one year. During the breaking phase, KAM was reduced to 85% of preoperative levels at six months but increased to 94% at one year. Knee adduction impulse and moments during the propulsive phase were reduced to 65% and 74% of preoperative levels, respectively, at six months, and remained reduced at one year. Preoperative static knee alignment increased from 2.2° varus to 3.5° valgus at six months and one year. Knee society scores and function scores improved from pre-operation to six months and from six months to one year. Also gait velocity increased
11% from pre-operation to one year. Although symptoms and function seem to improve, Orishimo et al. (2012) suggests that knee adduction moments reduced to normative levels at six months post-operation but might return to pre-surgical levels after one year. Orishimo et al. (2012) also found that static alignment of TKA doesn’t correlate with a decrease of KAM implying that dynamic observation is more important in evaluating knee adduction moment and should be considered. 20

**Hip Mechanics and Knee Adduction Moment**

With a possible return of KAM to pre-TKA levels one-year post-TKA20, other variables that have affected KAM during OA may still be present even after TKA. Several authors propose potential influence from proximal joints on KAM such as biomechanical factors at the hip joint, hip adduction moment (HAM) being one of them1,5,7. Mundermann et al. (2005) compared the loading characteristics of the ankle, knee, and hip joints in 42 patients with bilateral medial knee OA of varying severities and 42 matched controls. Kinematic and kinetic data were collected from self-selected gait trials. A multivariate analysis of variance was used to detect difference between gait patterns between groups, with an ANOVA and post hoc tests done for all significant findings. In terminal stance, patients with OA had 18.2% smaller maximum inversion moments at the ankle. The more severe OA group had a 6.0° greater varus mechanical axis alignment than the less severe OA group. Patients with OA had a 5.3° more extended knee position at heel strike than control subjects. This difference was more pronounced in the group of patients with less severe knee OA than the group with more severe OA. Following heel strike, maximum abduction moments at the knee were increased 93.3% for the group with knee OA compared to controls. Patients with less
severe knee OA had greater maximum knee abduction moments than the group with more severe OA when compared to matched controls. The less severe OA group had significantly lower second peak KAM than their controls and the more severe OA group. The more severe OA group had greater first peak KAM than their controls during midstance and terminal stance phases. The group of all patients with OA walked with 18.1% greater hip flexion compared to controls. Following heel strike, maximum hip abduction moments were increased 100.7% in all patients with knee OA compared to controls. The group of patients with more severe knee OA had lower first and second peak HAM compared with their matched controls. Mundermann et al. (2005) also reported all vertical ground reaction forces to be higher in all patients with knee OA than their matched controls with magnitude increasing as severity increased as well as greater lateral ground reaction forces. The less severe OA group experienced HAM during stance phase similar to their matched controls while the more severe OA group experienced lower HAM than their respective controls. Mundermann et al. (2005) also suggests that all patients with knee OA tend to initiate ground contact with a more extended knee than controls and experience greater ground reaction force vertically and laterally. 

Chang et al. (2005) examined the relationship between peak internal hip abduction moment and ipsilateral medial tibiofemoral OA progression. Subjects included individuals in the Mechanical Factors in Arthritis natural history study at Northwestern University selected from community sources. Participants (n=57) with at least one knee having OA based on K/L score had bilateral radiographs taken at baseline and performed kinematic and kinetic gait analysis at baseline. Assessment of OA progression included
bilateral radiographs taken at a follow-up 18 months and K/L scoring. Results show peak internal hip abduction moment occurs at early stance phase of gait. Odds of medial OA progression were reduced by 50% with an additional 1 unit of internal hip abduction moment. Non-progressing knees had greater peak internal hip abduction moment than the progressing knee. Chang et al. (2005) suggest that based on these results, greater internal hip abduction moment on the ipsilateral leg is associated with a decreased progression rate of knee OA.  

Astephen et al. (2008) also investigated how lower extremity mechanical factors influence progression of knee osteoarthritis. In a cross-sectional study, 60 control subjects, 60 with moderate knee OA, and 61 severe OA were screened for gait testing. Severe patients were distinguished from moderate by the need for surgical candidates as well as significantly greater WOMAC scores and K/L scores. The majority (76%) of severe subjects had predominantly medial knee compartment OA but most showed degenerative changes in all compartments. Kinematic and kinetic gait analysis was performed at self-selected walking speed. The Only severe group changes included reduced knee extension moments and reduced knee internal rotation moments in late stance phase as well as smaller ranges of joint motion at all three lower extremity joints and reduced peak knee flexion angles. All OA group changes included reduced knee flexion moments in early stance and higher mid-stance KAM. Also, reduced early stance peak HAM in the All OA group. Both OA groups had higher late stance hip flexion moments. Other parameters such as BMI patterns and walking speed were consistent with other research. Overall, in the frontal plane, Astephen et al. (2008) found the all OA group showed reduced early stance peak HAM, and higher midstance KAM\(^1\).
Huang et al. (2008) investigated kinematics and kinetics during walking gait in 15 mild bilateral knee OA patients, 15 severe bilateral knee OA patients, and 15 control subjects. One-way ANOVA’s were used to analyze dependent variables between OA and control groups. No significant differences in gait speed, cadence, step widths, and stride lengths were found. During heel-strike, the severe OA groups exhibited a more extended knee, plantarflexed ankle, and abducted hip compared to healthy subjects. Similar results were found in the mild OA group except not statistically significant. Knee abduction was smaller in the OA groups than the healthy group during single limb stance. Pelvic anterior tilt was found in the beginning of single limb stance for the severe OA group and at the end of single limb stance for both OA groups. The OA groups had greater hip extensor moments during single limb stance, smaller peak knee extensor moments during early stance, and decreased peak ankle dorsiflexor moments following heel-strike compared to the healthy group. The severe OA group exhibited higher HAM in midstance and terminal stance phases than the control group while the mild OA group had similar HAM to the control group. The severe OA group also exhibited higher early and late peak KAM than healthy subjects while mild OA group was similar to the healthy subjects. All of the OA subjects had smaller ankle internal rotation moments than the control group. Huang et al. (2008) suggest their results of gait speed did not contribute to the altered mechanics of the lower limb in the frontal plane, instead, compensatory gait strategies were adopted in the frontal plane to maintain the gait speed in the OA group. They also suggest that frontal plane peak joint moments in the knee and hip may agree with previous authors, except in the second peak HAM where they found greater levels in the severe OA group compared to controls which agrees Linley et al. (2010).
**Hip Mechanics and Hip Abductor Muscle Strength**

Due to HAM being a net external moment and its equal but opposite internal hip abduction moment receiving attention from Chang et al. (2005), hip abductor muscle strength has been proposed as being a potential influencing factor of KAM and HAM. Rutherford et al. (2009) recruited 22 healthy individuals to examine relationships amongst HAM, hip abductor muscle strength, hip abductor muscle activation and other related variables. Subjects had maximal voluntary isometric contraction performed along with gait kinematic and kinetic analysis and electromyography (EMG). Four forward stepwise regression models were used and variance inflation factors were used to assess multi-collinearity and the suitability of the regression model was evaluated by examining the plots of the residuals against the predicted values. Hip adduction moment occurred at approximately 15% of the gait cycle at 1.63Nm/kg and the dip of the characteristic double hump occurred at approximately 35% of the gait cycle at 0.80Nm/kg. The EMG waveform of the gluteus medius peaked at 8% of gait cycle with a 70% of maximal voluntary isometric contraction. The second smaller peak at 29% of maximal voluntary isometric contraction occurred around the same point in the gait cycle with the dip of HAM. Variability in HAM during initial stance was mostly explained by the mass (80%) and self-selected velocity (10%) of the subject. Hip abductor strength explained 10.5% of the variability in the HAM mid-stance magnitude while subject mass explained 52% where strength had a negative relationship and mass had a positive relationship. These results suggest that hip abductor strength does not explain variability in the initial peak of HAM but may explain some variability during mid-stance.
Another study by Hinman et al. (2010) compared the strength of hip musculature in 89 knee OA patients to 23 control subjects. Maximal isometric strength of the hip abductor, adductor, internal rotator, external rotator, flexor, and extensor muscles was measured for all subjects with a hand held dynamometer. Symptom levels of knee OA were assessed with WOMAC scores. Independent t-tests and chi-square tests were used to compare descriptive characteristics between groups and Spearman’s rho correlations were performed for muscle strength and OA severity data. Weaknesses in all muscle groups were found in the OA group after adjusting for age and sex. Muscle strength was not correlated with radiographic disease severity with the exception of hip abductor strength. These results do not determine whether or not weakness in the hip musculature precedes development of knee OA, however, significant weakness exists in knee OA patients supporting strengthening rehabilitation efforts.22

Further examining the effects of hip abductor muscle strength and activation, Henriksen et al. (2009) investigated the mechanics of experimentally induced pain and reduced function in the gluteus medius during gait in 15 healthy individuals. Previous studies have suggested weakness in the hip abductor muscles would lead to an increase in KAM due to changes in frontal plane GRF5,7. The current study tested the hypothesis that impaired gluteus medius function would lead to kinematic and kinetic changes during gait, especially KAM. Subjects were tested on two days separated by at least one week. Each testing day included three series of walking trials with the first being a baseline trial at self-selected velocity. The second trial, which was randomized, was done five minutes after the baseline trial, immediately following an intramuscular saline injection that would cause pain (5.8% hypertonic) or a placebo (0.9% isotonic) causing
no pain. The third trial on a single day was done 20 minutes after the last of the testing trials after injection effects have subsided. Surface electromyography (EMG) electrodes were positioned along the muscles of the right leg. Baseline maximal voluntary isometric contraction (MVC) was measured prior to walking trials. During gait, trunk lean angles were defined in two ways: (1) the angle between the trunk and pelvis segments, and (2) the angle between the trunk segment and the global vertical axis. A post-hoc analysis was used for statistically significant results after initial repeated-measures and covariance statistical analysis. The hypertonic effectively produced pain and resulted in a reduction of peak gluteus medius EMG activity during gait trials. During pain, peak internal hip abductor moment was reduced by 0.05 Nm/kg, corresponding to a 6.4% reduction, compared to non-painful injections. A decrease in peak hip adduction angle was observed during pain and there was a decrease in maximum hip extension. During pain, the KAM was reduced by 0.02Nm/kg, corresponding to a 4.2% decrease compared to the placebo injection, and there was a decrease in midstance knee extension angle. Trunk lean angles towards the stance leg decreased by 0.4° in pain trials. The results of the current study contradict the hypothesis that decreased hip abductor muscle function would increase KAM. Temporal concurrence of the peak gluteus medius EMG activity and the first peak in hip and knee frontal plane moments may suggest these changes are due to impaired gluteus medius function and not trunk motion.21

Much like Henriksen et al. (2009) results21, Bennell et al. (2010) adds to the uncertainty and complexity of hip abductor strength’s association with KAM. Eighty-nine participants with knee OA underwent gait analysis with 45 of the subjects underwent a strengthening program to improve hip abductor and adductor strength. Seventy-six of
the participants completed the 12-week study with a follow-up data collection. Linear regression modeling was used to analyze the relationship between the variables including KAM, HAM, contralateral pelvic drop, ipsilateral trunk lean, and hip muscular strength. Contrary to results of previous studies, Bennell et al. (2010) observed an increase in KAM in the hip-strengthening group. There is a small but significant change in maximum contralateral pelvic drop where the strengthening group showed a 15% increase and controls a 7% decrease. Despite the increase in KAM, the strengthening group’s measures of pain and physical function significantly improved compared with the control group. The strengthening group increased in hip abductor and hip adductor strength significantly during the 12-week study. The hypothesis that this increase in strength would decrease the KAM but, KAM showed an increased in the intervention group although symptoms and function became better. Contradicting theories of previous authors\cite{5,7,17} suggesting that an increase in internal hip abduction moment (hip abductor strength) decreases KAM, Bennell et al. (2010) results adds more complexity to the relationship of contralateral pelvic drop, ipsilateral trunk lean, HAM, and KAM. The increase in hip abductor strength would theoretically improve contralateral pelvic drop\cite{17} and ipsilateral trunk lean\cite{8,13} but instead a small decrease in trunk lean and an increase in pelvic drop occurred and decreases in hip abductor strength might not lead to increased medial knee load\cite{23}.

**Pelvic Drop and Trunk Lean in Osteoarthritic Patients**

As proximal motions are proposed to alter during gait, pelvic drop and trunk lean may, combined, be of impact to the mechanics occurring at the distal knee joint. Takacs and Hunt (2012) examined the effects of conscious contralateral pelvic drop and
contralateral trunk lean with pelvic drop on KAM in 20 healthy individuals. Participants had kinematic and kinetic data taken while single limb standing with opposite leg at 90° knee flexion on a force plate in three positions for three seconds: (1) pelvis and trunk in a normal neutral position, (2) self-selected pelvic drop of the non-stance side, and (3) self-selected pelvic drop of non-stance side and trunk lean towards non-stance side. Repeated ANOVAs and post-hoc analyses were used to analyze data. Conscious pelvic drop and pelvic drop with trunk lean trials produced significant changes in pelvic obliquity and trunk lean angles with no significant differences in pelvic obliquity between the two conditions. Compared to the normal trials, the pelvic drop trials and pelvic drop and trunk lean trials both produced significant increases in KAM. Frontal plane GRF did not change significantly amongst the trials whereas the knee lever arm and COM-COP distances increased significantly for the experimental trials. These results suggest that while stationary single limb standing, contralateral pelvic drop may shift the COM medially from the stance limb increasing KAM due to a longer knee lever arm. Also, the increase in KAM with the contralateral drop and contralateral trunk lean condition may support evidence that ipsilateral trunk lean may reduce KAM due to reduction of the knee lever arm.17

Trunk sway in knee OA patients, normally towards the stance leg during gait, has been observed as a compensatory motion to decrease pain during gait8,13. Mundermann et al. (2008) investigated medio-lateral trunk sway in 19 healthy subjects to determine if the effects of the increased trunk sway are decoupled from a mechanism of gait compensation used by knee OA patients. Walking trials were performed at self-selected speed with increased medio-lateral trunk sway practiced prior to testing. Kinematic and
kinetic data were collected in a similar manner to previous studies⁵,⁶. Separate repeated measures Student’s t-tests were used to detect significant differences amongst the variables. Bonferroni correction was then applied to the significance level to account for multiple comparisons. Walking with increased trunk sway reduced KAM an average of 65% compared with normal trunk motion. On average, subjects landed with the knee in a more flexed position. No differences were observed for the lateral GRF and the axial loading rates at the lower extremity joints between trunk sway and normal. Average increase of knee and hip abduction moments were found trunk sway were 60.1% and 55.3% respectively. Also similar to the knee, the first peak HAM was reduced for all subjects around 57.1%. These changes were observed despite subjects walked with a similar speed for both conditions and increased medio-lateral trunk sway. These results show that within the healthy individual, trunk sway can reduce the KAM and HAM during gait without significant differences in the lateral GRF and axial loading rates at the ankle, knee, and hip.¹³

Hunt et al. (2008) examined lateral trunk lean during gait in 120 patients with medial compartment knee OA. Participants pain level was assessed using the WOMAC index, had lower limb alignment measured using double-limb standing anteroposterior radiographs, and had gait analysis performed at their typical walking speed. Pearson correlation coefficients were used to examine the relationships amongst the dependent variables and sequential linear regression was used to evaluate variance. Complete data from 114 patients were used in the primary analysis. Double hump peaks in the KAM waveform occurred at approximately 31% and 76% of stance. Pelvic obliquity angles indicated small amounts of contralateral pelvic drop (2.67°) or rise (3.07°) during stance.
Participants exhibited less toe-out (7.71° vs. 8.82°) and more trunk lean (3.11° vs. 1.90°) at the time of the first KAM peak compared to the second peak. Mechanical axis angle had a significant positive correlation while toe-out and lateral trunk lean had significant negative correlations with first and second peak KAM. Lateral trunk lean was also significantly correlated to WOMAC pain scores. In the first peak KAM, 50% of the variation was explained by mechanical axis (25%), WOMAC pain score, gait speed, toe-out angle, and lateral trunk lean. For the second peak KAM, 60% of the variation was explained by the mechanical axis angle (38%), WOMAC pain score, gait speed, toe-out angle, and lateral trunk lean angle. These results suggest that patients with medial compartment knee OA walk with varying amounts of lower limb rotation and trunk lean. The magnitude of lateral trunk lean, Hunt et al. (2008) observed, had the highest correlation with the first and second peak KAM amongst the kinematic variables investigated potentially indicating a strong relationship.\(^8\)

As trunk lean and pelvic obliquity are influential motions impacting KAM and HAM magnitudes, Linley et al. (2010) assessed biomechanical motion of the trunk and pelvis in 40 control and 40 medial knee OA subjects. Gait analysis was performed on all subjects at self-selected walking speed. Trunk and pelvis motion was observed in two ways, the orientation of the thoracic tilt with respect to the coordinate system of the lab (thoracic tilt-lab) and the thoracic tilt with respect to the coordinate system in the pelvis (thoracic tilt-pelvis), with positive reported as tilt over the stance limb. Student’s t-tests were used to detect differences between groups and discrete parameters were extracted from waveforms and analyzed. Principal component analysis was used to detect differences in waveform shapes and magnitudes amongst the definitions of trunk and
pelvic tilt. There were significant differences between the two groups in weight, BMI, gait speed, cadence, and double limb support time. Pelvic tilt, thoracic tilt-pelvis, HAM, and KAM displayed double peak curves although thoracic tilt-lab did not. In the OA group across the mid portion of stance (20-80% stance), at midstance (50% stance), and in the second peak, KAM and HAM were higher in the OA group than control group. The first peak KAM was also significantly higher in the OA group. Discrete measures of pelvic and thoracic tilt showed the OA group to have greater peak and mean values than the control group however they weren’t significant. Significant group differences in range of motion in pelvic and thoracic tilt were detected by PCA, also finding that small motion pattern differences between the two groups. At approximately 25% of stance, lateral pelvic tilt over the stance limb reaches the first peak while the second peak shows a tilt over the swing limb at about 75% of stance with differences between groups found in the range of motion and the variation in neutral position. For thoracic tilt-lab motion, the OA group is shown to have more motion, however, the thoracic tilt-pelvis shows greater range of motion during stance phase in the control group. Also, during very late stance, an increased thoracic tilt over the swing limb was coupled with a pelvic tilt over the stance limb, with the thoracic tilt over the swing limb being more pronounced in the OA group. These results lead Linley et al. (2010) to believe OA subjects may move their trunk and pelvis more as a single unit whereas control subjects balance motions out between the two segments. This may indicate that lateral trunk lean is a combination of both pelvic and thoracic tilt.
APPENDIX A: Informed Consent
INFORMED CONSENT
To Participate in a Research Study

Department of Kinesiology and Rehabilitation Science, University of Hawaii at Manoa
1337 Lower Campus Road, PE/A Complex Rm. 231, Honolulu, HI 96822
Phone: 808-956-7606

I. INVESTIGATORS
Principal Investigators: Cris Stickley, PhD, ATC

Investigators: Samantha Andrews, MS, ATC; Matthew Jones, ATC;
Chris Ang, ATC; Christen Black, ATC; Grace Wang, ATC

II. TITLE
A Biomechanical Analysis of Gait Retraining Tools to Develop a
Rehabilitation Protocol for Knee Osteoarthritic Patients

III. INTRODUCTION
The following information is being provided to help you decide if you would like
to participate in this study. This form may have words that you do not understand. If you
have questions, please ask us. The purpose of this study is to investigate the risk factors
for total knee arthroplasty failure.

IV. DESCRIPTION OF PROCEDURES
You will be asked to report to the University of Hawaii at Manoa Gait Lab
(Sherriff 100) for a one-time data collection. When you arrive at the Gait Lab, you will
be asked to perform three tasks: (1) walk for six meters at a self-selected speed, 5-8
times; (2) walk for six meters with an adjusted speed, 10-16 times; and (3) receive verbal
cues from the researcher to adjust your walking and walk six meters at a set speed, 20-30
times. The entire procedure will take approximately 45 minutes.

V. RISKS
Due to the low level of physical activity involved, the risk of injury is comparable
to your routine activities of daily living. Although we have a fall prevention system, there
is a chance of falling during the walking test. There is a very remote chance of cardiac
arrest and/or death.

The investigators are NATABOC certified athletic trainers and First
Aid/CPR/AED trained. In the event of any physical injury from the research, only
immediate and essential medical treatment is available including an AED. First Aid/CPR
and a referral to a medical emergency room will be provided. In the event of any
emergency incidence outside the lab as a result of this research, contact your medical
doctor and inform the principal investigators: Samantha Andrews, MS, ATC at 843-754-
1468 or Cris Stickley, PhD, ATC, at 513-259-4666. You should understand that if you
are injured in the course of this research process that you alone will be responsible for the
costs of treating your injuries.
VI. **BENEFITS**
You may not receive direct/immediate benefits. However, you will obtain information regarding your walking gait.

VII. **COMPENSATION**
No compensation will be given.

VIII. **CONFIDENTIALITY**
Your research records will be confidential to the extent permitted by law. Agencies with research oversight, such as The University of Hawaii Committee on Human Studies, have the right to review research records.

An identification number will be used to identify you during the study, which will be known only to you and study personnel. In addition, all data and subject (identity) information will be kept under lock and key in the Department of Kinesiology and Rehabilitation Science at the University of Hawaii at Manoa. These materials will be permanently disposed of in a period not longer than 5 years. You will not be personally identified in any publication arising from this study. Personal information about your test results will not be given to anyone without your written permission.
IX. CERTIFICATION

I certify that I have read and I understand the foregoing, that I have been given satisfactory answers to my inquiries concerning the project procedures and other matters and that I have been advised that I am free to withdraw my consent participation and to discontinue participation in the project or activity at any time without prejudice.

I herewith consent to participate in this project with the understanding that such consent does not waive any of my legal rights, nor does it release the principal investigator or institution or any employee or agent thereof from liability for negligence.

I attest that I am not currently limited from full participation in my chosen sport due to injury.

I attest that I do not believe that I am currently pregnant.

If you have any questions related to this study, please contact any of the principal investigators: Samantha Andrews MS, ATC, at 843-754-1468 or Cris Stickley at 513-259-4666 at any time.

___________________  ________________________________
Participant’s Printed Name                                              Signature of Participant

Date

If you cannot obtain satisfactory answers to your questions, or have complaints about your treatment in this study, please contact: Committee on Human Subjects, University of Hawai‘i at Manoa, 1960 East-West Rd., Biomed Bldg, Ste. B-104, Honolulu, Hawaii 96822, Phone (808) 956-5007.
APPENDIX B: Institution Committee on Human Studies Application
Application for New Approval of a Study Involving Human Subjects
University of Hawaii Human Studies Program
Biomedical Bldg, Room B-104, 1960 East-West Road, Honolulu, HI 96822
Telephone: (808) 956-5007

Date: ____
P.I. Name: Dr. Cris Stickley E-mail: cstickle@hawaii.edu Phone: 513-259-4666

Department: Kinesiology and Rehabilitation Science Campus: Manoa
☑ Faculty or Staff ☐ Student

Administrative Contact: Samantha Andrews Supervising Professor: Cris Stickley
Admin. Contact e-mail: sandrews@hawaii.edu Supervising Prof. e-mail: cstickle@hawaii.edu

*Required Training in Human Subjects Protection - P.I.(s) and key personnel:
Researchers proposing non-exempt projects involving human subjects must complete appropriate training.
☑ Yes PI completed Human Subjects Protection Training Date
Completed: ______
☐ No

☐ If applicable - Key Personnel completed Human Subjects Protection Training Date
Completed: ______
☐ No

If Checking "No", these training requirements must be completed. This application may not be approved until documentation of training has been received by the HSP office.
(For more information: http://hawaii.edu/irb/html/training_online.php)

Institutional Biosafety Committee (IBC) Review:
Researchers proposing projects involving r-DNA molecules or any biological materials, toxins, agents, etc., referred to as biological commodities, must submit appropriate Biological Safety Program forms.

Does this project involve the use of biohazardous materials, recombinant DNA and/or gene therapy?
☐ Yes. If so, IBC approval must be obtained.
☑ No

Has the IBC approved the protocol?
☐ Approved Date
Approved: ______
Are there any other local IRBs reviewing this proposal? ☒ No ☐ Yes, Location:

Are there any other non-local IRBs reviewing this proposal? ☒ No ☐ Yes, Location:

Does this project involve Hawaii State Department of Health data? ☒ No ☐ Yes

Does this project involve Hawaii State Department of Education personnel, facilities or data? ☒ No ☐ Yes

Project Title: A Biomechanical Analysis of Gait Retraining Tools to Develop a Rehabilitation Protocol for Knee Osteoarthritic Patients

Proposed Sponsoring or Funding Agency (If any): ______

Complete Agency address: ______

Project funding has been approved: ☐ Yes ☒ No

1. Summarize your proposed research. Outline objectives and methods.

Several biomechanical parameters, such as external knee adduction moment, have been linked to the progression and severity of osteoarthritis. End stages of osteoarthritis require total knee arthroplasty, replacing the diseased joint surfaces and re-establishing neutral alignment of the lower extremity. However, previous biomechanical studies have reported limited improvement in important gait parameters, perhaps placing the patient at a greater risk for implant failure. Limited research has been conducted on gait retraining programs for osteoarthritic patients after surgery, with the main focus being on the use of virtual reality. This equipment is expensive and only available to the patient during rehabilitation sessions. Therefore, this study is designed to investigate gait rehabilitation tools, such as adjusted walking velocity and verbal cues, and their effect on gait biomechanical parameters. With this information, we hope to develop a gait retraining program for those recovering from total knee arthroplasty.

Biomechanical analysis will be conducted at the University of Hawaii Gait Laboratory. Walking gait biomechanics will be collected using 27 retroreflective markers placed in accordance with a Vicon plug-in-gait model and a three-dimensional (3D) motion capture system consisting of 13 Vicon motion capture cameras and Vicon Nexus software (Vicon, Inc., Centennial, CO), and two force plates (Advanced Mechanical Technology Incorporated, Boston, MA) embedded flush with the floor. Kinematic data will be collected at 240 Hz and will be time synchronized with kinetic data collected at 480 Hz.
then smoothed using a Woltering filter (MSE 10). All data will be processed using Plug-in Gait (Vicon, Inc., Centennial, CO, USA) and in-house software. Participants will be asked to walk barefoot across the four-meter data collection field at a self-selected velocity recorded by infrared timers (Speed Trap II, Brower Timing Systems, Draper, UT, USA). A successful walking trial includes placement of the entire foot on the force plate without a visible change in gait in an attempt to target the force plate with the appropriate foot. Participants will perform the minimum number of trials necessary to obtain three acceptable trials on their dominant leg. Walking velocities will then be calculated 25% above and below their self-selected velocity and participants will repeated the previously described walking trial protocol. All moments will be reported as external moments, normalized to body mass. For the following protocol to assess verbal cues and their effects on gait parameters, participants will be asked to walking within 10% of their self-selected walking velocity. Each participant will be given verbal cues to adjust their walking during gait analysis. No instruction beside the verbal cue will be given to ensure consistency between all participants. After the verbal cue has been given, participants will complete the minimum number of trials necessary to obtain three acceptable trials on their dominant leg. Verbal cues will be given in a random order for each participant and will include:
- “Walk with your knees apart.”
- “Walk with your knee caps facing forward.”
- “Walk with your toes out.”
- “Walk with your toes pointed forward.”
- “Walk with your pelvis level.”

2. Summarize all involvement of humans in this project (who, how many, age, sex, length of involvement, frequency, etc.) and the procedures they will be exposed to. Attach survey instrument, if applicable.

A one-time data collection will be conduction to assess the affects of walking velocity and specific verbal cues have on biomechanical risk factors for the development of osteoarthritis previously identified in research. Inclusion criteria for all participants included: 1) between 20 and 40 years of age, 2) no previous history of lower extremity fracture, osteotomy, or joint replacement, 3) no lower extremity injury within the last six months and 4) able to walk continuously for 10 minutes. A convenience sample of ten males and ten females from the community will be included in this study. Prior to the study, all participants signed informed consent forms approved by the Institution’s Committee on Human Studies and Western Institutional Review Board.

Indicate whether your research involves any of the following:
☐ Minors  ☐ Pregnant Women  ☐ Physically Disabled
☐ Prisoners
Impaired Decision-making Capacity  Other vulnerable groups
(Please specify below)

3. Research involving humans often exposes the subjects to risks: For the purpose of this application, "risk" is defined as exposure of any person to the possibility of injury, including physical, psychological, or social injury, as a consequence of participation as a subject in any research. Research risk is further defined as risks related to research activity that are over and above ordinary risks of daily life.

a. Check each of the possible risks to human subjects that apply to your project:
   - Physical trauma or pain
   - Deception
   - Experimental diagnostic procedures
   - Side effects of medications
   - Loss of privacy
   - Experimental treatment procedures
   - Contraction of disease
   - Worsening of illness
   - Other – explain below
   - Psychological pain
   - Loss of legal rights

b. Check procedures that will be used to protect human subjects from risks:
   - M.D. or other appropriately trained individuals in attendance
   - Sterile equipment
   - Precautions in use of stressor or emotional material (explain below)
   - When deception is used, subjects are fully informed as to nature of research at feasible time (explain below)
   - Procedures to minimize changes in self-concept (explain below)
   - Confidentiality of subjects maintained via code numbers and protected files
   - Certificate of Confidentiality
   - Anonymity - no personally identifiable information collected
   - Others-- explain below

c. Has provision been made to assure that human subjects will be compensated for expenses incurred as a direct or indirect result of participating in this research?
   - Not applicable
   - No - The following language should appear in the written consent form: I understand that if I am injured in the course of this
research procedure, I may be responsible for the costs of treating my injuries.

☐ YES, explain:

d. Are there non-therapeutic tests that the research subjects may be required to pay for?

☒ Not applicable
☐ No
☐ Yes - explain below.

If marked yes, the following language should appear in the written consent form: I understand that I may be responsible for the costs of procedures that are solely part of the research project.

4. Describe mechanisms you will use for safety monitoring: How will you detect if greater harm is accruing to your subjects than you anticipated? What will you do if such increased risk is detected? Be sure that you address, at minimum each of the risks you checked in item 3.

Due to the low level of physical activity involved, the risk of injury is comparable to normal activities of daily living. The Human Performance and Biomechanics lab is equipped with a fall prevention system; however there is chance of falling during the walking and jogging tests. There is a very remote chance of cardiac arrest and/or death. These risks are comparable to routine rehabilitation and activities of daily living, and will not affect the subject’s rehabilitation and recovery. The investigators are First Aid/CPR/AED trained and/or National Athletic Trainers’ Association Board of Certification certified athletic trainers. In the event of any physical injury from the rehabilitation program or gait analysis, only immediate and essential medical treatment is available including an AED. First Aid/CPR and a referral to a medical emergency room will be provided. In the event that the subject should be injured or become ill as a direct result of participation in this study, medical care would be provided at no cost to the service member through the Veteran's Affairs medical care system. They will not receive any injury compensation; only medical care. The subject should understand that this is not a waiver or release of legal rights.

5. Briefly describe the benefits that will accrue to each human subject or to humankind in general, as a result of the individual’s participation in this project, so that the committee can access the risk/benefit ratio. First, describe the DIRECT benefits, if any, to the participants in your study. Then, describe possible benefits that are more general.

Participants will not receive direct/immediate benefits. However, information regarding walking gait will be provided.
6. **Participation must be voluntary: the participants cannot waive legal rights, and must be able to withdraw at any time without prejudice.** Indicate how you will obtain informed consent/assent:

- Subject (or Parent/Guardian) reads complete consent/assent form & signs (‘written’ form)
- Oral briefings by P.I. or project personnel, with simple consent form (‘oral’ form). Explain below the reason(s) why a written consent form is not used
- Other- explain

---

*I affirm that the above and any attachments are a true and accurate statement of the proposed research and of any and all risks to human subjects. Furthermore, I will submit a modification form documenting any future changes to this study.*

**Signed:** ________________________________  **Date:** _____

**Principal Investigator**

**Signed:** ________________________________  **Date:** _____

**Supervising Professor (required if PI is a student)**

---

*Submit an electronic (.doc or .pdf format preferred) copy of this application form with the following attachments to uhirb@hawaii.edu:

- Consent/assent form(s)
- Recruitment materials
- Any other information to be read or presented to the study subjects
- Verbal information to be given if short form (consent)
- Survey instrument(s) (Please consult with the Human Studies Program staff if providing the survey instrument presents a problem.)
- Proposal/Protocol (If appropriate. Do not attach a grant application or a contract.)
- Documentation that Human Subjects Training requirements have been met by the study PI(s).
- If applicable, documentation that Human Subjects Training requirements have been met by all key personnel. Key personnel should be listed on a separate page, with the dates of completion.
- If applicable, an electronic copy (do not include hard copy) of the Investigator’s Brochure (IB) provided by the study sponsor.

*In addition to the e-mail submission, please mail or deliver two hard copies (collated) to:*
This is for proposals needing full Committee or expedited review. If this is a project that may qualify for exempt approval, hard copy is not required; the email submission will be sufficient. Please check with Human Studies Program staff if you have questions about the level of review of your proposal.
APPENDIX C: Anthropometric Data Collection Sheet
**Anthropometric Data**

Subject ID#: _______________  Date________

Age_______________  Gender: F / M

Dominant Leg: L / R

**Vicon/Nexus Measurements**

<table>
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<th>Value</th>
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</tr>
<tr>
<td>Age (yrs)</td>
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<td>Left leg length (mm)</td>
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</tr>
<tr>
<td>Left knee width (mm)</td>
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<tr>
<td>Left ankle width (mm)</td>
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<tr>
<td>Right leg length (mm)</td>
<td></td>
</tr>
<tr>
<td>Right knee width (mm)</td>
<td></td>
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<tr>
<td>Right ankle width (mm)</td>
<td></td>
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</tbody>
</table>
APPENDIX E: Walking Data Collection Form
Gait Retraining  
Data Collection Sheet  
Walking Velocity

Dominant Leg: ________________________________

<table>
<thead>
<tr>
<th></th>
<th>Self-Selected Speed</th>
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</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td></td>
</tr>
<tr>
<td>Trial 2</td>
<td></td>
</tr>
<tr>
<td>Trial 3</td>
<td></td>
</tr>
</tbody>
</table>

Walking Trials: 1 2 3 4 5 6 7 8 9 10

Self-Selected Pace Average: ____________

25% Increase: _______________  ± 10% Acceptable Range: _______________

<table>
<thead>
<tr>
<th></th>
<th>25% Increase</th>
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<tbody>
<tr>
<td>Trial 1</td>
<td></td>
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<tr>
<td>Trial 2</td>
<td></td>
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<tr>
<td>Trial 3</td>
<td></td>
</tr>
</tbody>
</table>
Walking Trials: 1 2 3 4 5 6 7 8 9 10

25% Decrease: _______________ ± 10% Acceptable Range:

__________________

<table>
<thead>
<tr>
<th></th>
<th>25% Decrease</th>
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<tbody>
<tr>
<td>Trial 1</td>
<td></td>
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<tr>
<td>Trial 2</td>
<td></td>
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<tr>
<td>Trial 3</td>
<td></td>
</tr>
</tbody>
</table>

Walking Trials: 1 2 3 4 5 6 7 8 9 10
REFERENCES


