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Fort Detrick, Maryland  21702-5012

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**14. ABSTRACT**
The goals of this project are to identify exercises that maintain intact limb knee and hip joint and cartilage tissue loads at safe levels and, consequently, enhance the quality of life (QoL) via prevention of intact limb joint arthritis for military transtibial amputees. Progress includes the following. 1) Purchased, installed, and developed protocols for instrumentation needed for motion analysis studies. 2) Tested 16 out of 20 subjects in gait, cycling, and elliptical training experiments. 3) Developed analytical methods to obtain accurate knee joint kinematics (while minimizing errors due to soft tissue artifact and crosstalk); analysis of tested subjects underway. 4) Developed analytical methods to obtain ground reaction, pedal reaction, and knee joint loads; analysis of tested subjects underway. 5) Conducted eight knee MRI scans with finite element analyses underway. At the end of year 2, results and findings have been presented or submitted as nine conference papers.

**15. SUBJECT TERMS**
Amputee, prosthesis, knee, hip, biomechanics, cartilage, arthritis, finite element analysis

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1. **INTRODUCTION:** Abnormal biomechanics is a risk factor for knee joint osteoarthritis (OA) and is likely related to joint pain and OA among transtibial amputees. Although lower limb joint loading during gait for patients with high risk for OA has been examined, there are a lack of studies on joint loading for other fitness sustainment exercises and on predicting cartilage tissue loads of lower limb prosthesis users. The goals are to identify exercises that maintain intact limb knee and hip joint and cartilage tissue loads at safe levels and, consequently, enhance the quality of life (QoL) via prevention of intact limb joint OA for military transtibial amputees. The overall hypothesis is that intact limb joint and cartilage tissue loads depend on disability status (amputee vs. control) and exercise type (walking vs. cycling vs. elliptical training). Specific Aim 1 is to conduct motion analysis experiments and calculate intact limb knee and hip joint loads in amputee and control group subjects. Specific Aim 2 is to develop and use subject-specific finite element models to calculate intact limb knee joint cartilage loads in amputee and control group subjects.

2. **KEYWORDS:** Amputee, prosthesis, knee, hip, biomechanics, cartilage, arthritis, finite element analysis

3. **ACCOMPLISHMENTS:**
   **What were the major goals of the project?**

   Objective 1: Calculate knee and hip joint loads for walking, cycling, and elliptical training exercises.
   *Task 1.1*: Recruitment of n=10 amputee and n=10 control group subjects. Target date: 1/13/2018. Completion %: 85.
   *Task 1.2*: Motion analysis experiments with amputee and control group subjects. Target date: 1/13/2018. Completion %: 80.
   *Task 1.3*: EMG-driven inverse dynamic (ID) analyses with OpenSim for amputee and control group subjects. Target date: 1/13/2019. Completion %: 40.
   *Task 1.4*: Statistical analyses of knee and hip joint contact resultants for amputee and control group subjects. Target date: 1/13/2019. Completion %: 10.

   Objective 2: Calculate knee joint cartilage tissue loads for walking, cycling, and elliptical training exercises.
   *Task 2.1*: Conduct MRI scans of intact limb knee joints of n=3 amputee and n=6 control group subjects. Target date: 1/13/2018. Completion %: 89.
   *Task 2.2*: Develop solid models of the intact limb knee joints for n=3 amputee and n=3 control group subjects. Target date: 1/13/2019. Completion %: 67.
   *Task 2.3*: Develop FE models of the intact limb knee joints for n=3 amputee and n=3 control group subjects. Target date: 1/13/2019. Completion %: 33.
   *Task 2.4*: Conduct FE model simulations for amputee and control group subjects. Target date: 1/13/2019. Completion %: 17.
   *Task 2.5*: Statistical analyses of knee joint cartilage tissue loads for amputee and control group subjects. Target date: 1/13/2019. Completion %: 17.

   **What was accomplished under these goals?**

Major activities.

Please see the Significant results and Appendix sections for more details; the Appendix contains a *Bibliography* for citations and related conference papers.

*Hiring students.* A total of 13 student research assistants were hired and trained.

*Equipment.* Equipment items (EMG system, extra walkway sections and force plate for gait analysis, elliptical trainer, load cells for elliptical trainer, motion capture cameras) were purchased, installed, and used in experiments. Protocols were developed for equipment use. All motion capture cameras were re-positioned and calibrated in order to improve the quality of motion capture data.

*Soft tissue artifact (STA) compensation.* We developed a state-of-the-art analytical technique to reduce STA-induced errors in measured anatomical knee angles during motion analysis. The analysis models a body segment (thigh, shank) as a pseudo-rigid body (PRB) i.e. a body that experiences only homogeneous deformations. The 7 markers on a body segment marker are represented as 35 triangular elements that are each modeled as PRBs. Using parameters which can measure deformation and the uniformity of movement of the triangular elements, we estimated the true underlying rigid body motion of the body segment. Experiments have been performed for both validation purposes and for testing control and amputee group subjects. Further, a standard Procrustes Solution (PS) method that reduces STA-induced errors has also been implemented for comparison of results. This work was presented in two conference papers [1,2].

*Crosstalk error compensation.* We developed a state-of-the-art analytical technique to reduce crosstalk errors in measured anatomical knee angles during motion analysis using a statistical technique employing linear algebra call Principal Component Analysis (PCA). Experiments have been performed for both validation purposes and for testing control and amputee group subjects. This work was presented in two conference papers [3,4].

*Experiments and analysis of ground and pedal reaction forces.* Recruitment and testing of 10 control and 6 amputee group subjects in gait, cycling, and elliptical training have been completed. For those experiments, ground (gait) and pedal (cycling, elliptical) reaction forces have been analyzed. Recruitment of additional subjects is underway. This work was presented in two conference papers [5,6].

*ID analyses.* Initial pilot studies using ID were completed to obtain resultant knee joint loads in cycling. We completed development of our EMG-driven OpenSim protocols and related analyses to obtain knee joint contact loads for control and amputee group subjects is ongoing. Results including statistical analyses have been obtained from some control group subjects as well as from pilot studies that were used to develop and refine the protocols. This work was presented in two conference papers [3,7].

*Conduct MRI scans and develop solid knee models.* Completed for 5 of the 6 subjects needed.

*Develop FE knee models using MRI scans.* Completed for 1 of the 6 subjects needed. Resultant knee loads in gait and cycling for all 5 subjects tested have been used with the completed model to analyze cartilage tissue loads. Further, that model has been used to investigate the effect of cartilage tissue material model choice on FEA predicted cartilage tissue loads. Model development is nearing completion for the other subjects. This work was presented in two conference papers [8,9].

<u>Specific objectives</u>.

<u>Objective 1.</u> Calculate knee and hip joint loads for walking, cycling, and elliptical training exercises.
*Task 1.1.* (*recruitment).* Recruitment of 10 control and 7 amputee subjects completed. Recruitment of additional subjects underway.
*Task 1.2.* (*experiments).* Experiments with 10 control and 6 amputee subjects completed. Data inspection reveals that all experiments produced useable data.
*Task 1.3. (ID analyses).* PRB & PCA analysis with all tested subjects' data is ongoing. Meanwhile, EMG-driven OpenSim analyses are ongoing.
*Task 1.4. (statistics).* Statistical results have been obtained for knee kinematics from pilot studies and for ground (gait) and pedal (bicycling, elliptical) reaction forces for tested control and amputee group subjects.

<u>Objective 2.</u> Calculate knee joint cartilage tissue loads for walking, cycling, and elliptical training exercises.
*Task 2.1. (MRI scans).* MRI scans have been completed for 8 of the targeted 9 subjects.
*Task 2.2. (develop knee solid models).* Completed for 5 of the targeted 6 subjects.
*Task 2.3. (develop knee FE models).* Finite element model development is completed for 1 subject and nearing completion for 4 subjects.
*Task 2.4. (finite element analysis).* Fnite element analyses have been conducted for 1 subject and are underway for 4 subjects.
*Task 2.5. (statistics).* Statistical results have been obtained for completed finite element analyses.

<u>Significant results</u>.
The objectives and conclusions of the most relevant conference papers (7 out of 9 total) are briefly summarized below. Please see the full papers in the appendix for more details, including results, figures, and tables.

[2] S. Tucker, V. Profiti, S.J. Hazelwood, S.M. Klisch, Knee angles with soft tissue artifact correction for normal weight and overweight subjects in gait and cycling, in: World Congr. Biomech., 2018.

*Objectives*. This study used two analytical methods to correct for soft tissue artifact (STA): pseudo-rigid body (PRB) and Procrustes solution (PS) methods. The hypothesis was that knee angles will differ in gait but not in cycling between normal weight (NW) and overweight (OW) subjects.

*Conclusions*. NW and OW knee kinematics differed in gait but not in cycling. In gait, observed trends in OW subjects were similar to those found in OB subjects and suggests that osteoarthritis (OA) risk due to excess body weight may increase before body mass index

(BMI) reaches obese status.

[4] J.M. Skaro, H. Goel, S.J. Hazelwood, S.M. Klisch, Principal component analysis of gait and cycling experiments: crosstalk error reduction and corrected knee axes, in: Summer Biomech. Bioeng. Biotransport Conf., 2017.

*Objectives*. The aims are to (1) determine principal component analysis (PCA) corrected knee angles in gait and cycling for the same subjects and their corresponding flexion/extension (FE)-adduction/abduction (AA) correlations, (2) develop and implement an algorithm for determining PCA corrected knee FE and AA axes, and (3) compare the PCA corrected FE and AA axes for the same subjects to determine if they are similar in gait and cycling.

*Conclusions*. The statistical analyses demonstrated that there is substantial crosstalk between knee axes for gait and that PCA can correct for it. It is unsure if the corrected knee axes are similar between gait and cycling due to the large angles between corrected and uncorrected FE and AA axes. Thus, when using PCA to correct for crosstalk error in subjects performing exercises with high-flexion motions, these results suggest that PCA corrected axes from gait analysis may be used as a standard set of knee axes for other motions.

[5] G. Orekhov, E.A. Heyde, A.M. Robinson, S.J. Hazelwood, S.M. Klisch, Ground/pedal reaction forces and knee flexion angles for transtibial amputees in gait and cycling, in: Annu. Meet. Biomed. Eng. Soc., 2017.

*Objectives*. The objective of this study was to conduct motion analysis studies and compare ground reaction forces (GRFs) and pedal reaction forces (PRFs) and dominant leg knee flexion angles for transtibial (TT) amputee and control subjects.

*Conclusions*. The results reinforce that cycling may be a preferred exercise for rehabilitation and limiting osteoarthritis (OA) risk for TT amputees due to lower vertical and shear loads as compared to gait. Differences in knee flexion range for both exercises suggest that a compensation mechanism is in effect that could be partially responsible (among other factors such as knee flexor/extensor activity) for the increased risk of knee OA in TT amputees.

[6] G. Orekhov, E.A. Heyde, A.M. Robinson, S.J. Hazelwood, S.M. Klisch, Asymmetry in peak ground/pedal reaction forces for transtibial amputees in gait, cycling, and elliptical training, in: World Congr. Biomech., 2018.

*Objectives*. This study's hypotheses are that, at peak axial load, the magnitude of reaction forces will depend on subject (transtibial (TT) amputee, controls), exercise type (gait, cycling, elliptical) and leg (dominant, contralateral).

*Conclusions*. The results indicate that load asymmetries are present only in gait and that structured exercises that constrain user kinematics, such as cycling and elliptical training, can reduce asymmetry for TT amputees. Cycling may be a preferred exercise because of relatively low axial (AX) and total shear (TS) loads.

[7] M. V. Pottinger, K. Mavrommati, S.J. Hazelwood, S.M. Klisch, EMG-driven inverse dynamic analysis of knee contact forces during gait and cycling using OpenSim, in: Summer Biomech. Bioeng. Biotransport Conf., 2017.

*Objectives*. The objectives are to: (1) conduct motion analysis experiments and EMG-driven

OpenSim analyses for gait and cycling, (2) compare predicted tibiofemoral (TF) contact forces to published values, and (3) test for significant differences in maximum TF compressive forces in gait and cycling.

*Conclusions*. These findings reinforce the hypothesis that cycling results in relatively low TF joint compressive contact forces. A novel finding of this study is that OpenSim may be used to calculate knee contact forces during cycling as the results generally agreed with published results.

[8] G.T. Lane, M.G. Rumery, S.M. Klisch, S.J. Hazelwood, Human knee FEA model for transtibial amputee tibial cartilage pressure in gait and cycling, in: World Congr. Biomech., 2018.

*Objectives*. In this knee finite element analysis (FEA), we hypothesized that tibial cartilage contact pressure (CCP) depends on an individual's amputee status and exercise choice.

*Conclusions*. Lower cycling tibial CCP in the lateral compartment is due to lower varus-valgus moments as measured experimentally, causing reduced loading in the lateral compartment while increasing it in the medial compartment. Results indicate that regardless of subject type, cycling exercises may help preserve the lateral tibial cartilage over gait exercises.

[9] M.G. Rumery, G.T. Lane, S.M. Klisch, S.J. Hazelwood, Finite element analysis predictions of knee cartilage contact pressure in gait and dependence on material model choice, in: World Congr. Biomech., 2018.

*Objectives*. The objective of this study was to compare predicted cartilage contact pressures during gait for two elastic material model choices: Linear (LIN) and Neo-Hookean (NH).

*Conclusions*. NH model predictions have lower contact pressure and higher contact area than LIN model due to the effects of nonlinear behavior at high loads.

Other achievements.

None to report.

Stated goals not met.

Referencing the stated goals from our last quarterly report, the following were not met this past quarter.

1) The conference paper comparing EMG-driven inverse dynamics knee loading in gait, cycling, and elliptical training exercises was not completed. However, a paper comparing dominant and non-dominant axial and shear ground/pedal reaction forces between amputees and controls was submitted instead.

2) STA and crosstalk correction of knee angles has not been performed on all amputee and control subjects tested; these analyses are underway.

**What opportunities for training and professional development has the project provided?**

Training activities.

*Training: protection of human subjects*. Students and Faculty completed on-line CitiProgram training (course: Biomedical Researcher: Basic/Refresher) on protection of human subjects in research.

*Miscellaneous*. The research is being primarily conducted by B.S. and M.S. level students. Students were trained by faculty mentors on motion analysis experiments and analysis and general safety procedures throughout the period of report. Also, students were trained in CPR.

Professional development.
1) 4 students and 2 faculty funded to present conference posters at the Summer Biomechanics, Bioengineering Transport Conference, June 2017, Tucson AZ.
2) 3 students and 2 faculty funded to present conference posters at the Annual Meeting of the Biomedical Engineering Society, October 2017, Phoenix, AZ.
3) *OpenSim Virtual Workshop*. In October 2016, 6 students participated in the OpenSim virtual workshop for 1 week. In order to participate, the students presented a proposal before the workshop began and then submitted a summary slide after the workshop concluded. Goals included learning how to better use OpenSim for the required EMG-driven inverse dynamic analyses.

**How were the results disseminated to communities of interest?**
1) Results have been disseminated with 9 conference papers (see Appendix).
2) 3 local high school students were funded by a National 4-H Council sub-award to work in the HMB lab during the 2017 summer. The primary focus of this effort was to increase diversity among underrepresented groups in engineering. The high school students assisted HMB staff with several projects, including this project. Upon completion of these summer internships, the high school students presented HMB lab activities, including this project's activities, at 2 local elementary schools, 1 local high school, and 1 local youth 4-H club.

**What do you plan to do during the next reporting period to accomplish the goals?**
1) Recruit and test 2 additional amputee subjects to finish experiments.
2) PRB analysis: continue to perform PRB analysis to correct for STA for all control and amputee group subjects, in gait, cycling, and elliptical training.
3) PCA analysis: continue to perform PCA analysis to correct for crosstalk for all control and amputee group subjects, in gait, cycling, and elliptical training.
4) OpenSim analysis: continue to perform EMG-driven OpenSim for control and amputee group subjects in gait, cycling, and elliptical training.
5) FEA analysis: determine gait maximum contact pressure for n=3 control subjects using elastic and hyperelastic material models.
6) FEA analysis: determine gait and cycling maximum contact pressure for n=1 amputee subject.

4. **IMPACT:** Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as a result of the project relative to:

**What was the impact on the development of the principal discipline(s) of the project?**
The experimental and analysis results are still too preliminary to comment on this impact. However, the novel aspects of the project will improve understanding of knee biomechanics and, consequently, interventions aimed at normalizing biomechanics, reducing injury, and, ultimately, increasing QoL among both military and civilian transtibial amputees.

**What was the impact on other disciplines?**

The experimental and analysis results are still too preliminary to comment on this impact. However, the novel aspects of the project will improve analytical methods for obtaining accurate knee angles during motion analysis studies, and will generate new knowledge regarding knee biomechanics and cartilage tissue loading in bicycling and elliptical training exercises.

**What was the impact on technology transfer?**
Nothing to report.

**What was the impact on society beyond science and technology?**
Nothing to report; as results become finalized, this section will be updated as the societal impacts include recommendations for lifelong fitness sustainment exercises that maintain healthy knee loads for transtibial amputees.

## 5. CHANGES/PROBLEMS:

**Changes in approach and reasons for change**

**Actual or anticipated problems or delays and actions or plans to resolve them**
Problems with recruiting amputee subjects are ongoing as discussed in previous reports. Utilizing the California Hanger Clinic network has provided one potential candidate for the study in recent weeks. However, we increased our recruitment efforts in the last quarter and those efforts resulted in the recruitment of 3 and testing of 2 amputee subjects in that time (the third recruited subject is schedule for testing on 20 Jan 2018). Thus, we believe that continuation of our increased recruitment efforts will allow us to recruit the final 3 amputee subjects that are needed.

**Changes that had a significant impact on expenditures**
During 2017 we submitted, and received approval for, a budget modification. The greatest modification re-budgeted funds in order to purchase needed equipment, materials, and supplies that improved our motion analysis capabilities and, consequently, improving the quality and accuracy of our results.

**Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents**

**Significant changes in use or care of human subjects**
None to report since our last IRB approval.

**Significant changes in use or care of vertebrate animals.**
Not applicable.

**Significant changes in use of biohazards and/or select agents**
Not applicable.

## 6. PRODUCTS:

- **Publications, conference papers, and presentations**

  **Journal publications.**
  Results have been disseminated with 9 conference papers (see Appendix).

**Books or other non-periodical, one-time publications.**
Nothing to report.

**Other publications, conference papers, and presentations**.
Nothing to report.

- **Website(s) or other Internet site(s)**
  In the past year, our website was updated to reflect these efforts (e.g. see http://hmblab.calpoly.edu/projects/).

- **Technologies or techniques**
  *Identify technologies or techniques that resulted from the research activities. In addition to a description of the technologies or techniques, describe how they will be shared.*
  Nothing to report (see "other products" below).

- **Inventions, patent applications, and/or licenses**
  Nothing to report.

- **Other Products**

1) Custom PRB method software (MATLAB) and protocol to reduce STA for gait, cycling, and elliptical experiments. Related protocol in progress.
2) Custom PS (Singular Value Decomposition) method software (MATLAB). Related protocol in progress.
3) Custom PCA software (MATLAB) to reduce crosstalk error for gait, cycling, and elliptical experiments. Related protocol in progress.
4) Custom PCA software (MATLAB) to determine the PCA-corrected knee flexion and adduction axes.
5) Custom time sync code (MATLAB) to time sync EMG and motion capture data.
6) MATLAB script that de-identifies MRI scans to preserve patient privacy.
7) MATLAB script utilizing GIBBON to turn .stl surface meshes into tetrahedral computational meshes and write FEBio input files.

## 7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

| | |
|---|---|
| *Name:* | *Stephen Klisch* |
| *Project Role:* | *PI* |
| *Nearest person month worked:* | *6* |
| *Contribution to Project:* | *Dr. Klisch managed the project.* |
| *Funding Support:* | *Dr. Klisch is also funded by Cal Poly's Donald E. Bently Center for Engineering Innovation.* |

| | |
|---|---|
| *Name:* | *Scott Hazelwood* |
| *Project Role:* | *co-PI* |
| *Nearest person month worked:* | *5* |
| *Contribution to Project:* | *Dr. Hazelwood managed the finite element project aims.* |
| *Funding Support:* | *Also funded by the W.M. Keck Foundation.* |

*Name: Brian Self*
*Project Role: co-PI*
*Nearest person month worked: 1*
*Contribution to Project: Dr. Self is managing aims to instrument bicycle.*
*Funding Support: Also funded by the W.M. Keck Foundation.*

*Name: Jordan Skaro*
*Project Role: Undergraduate student*
*Nearest person month worked: 5*
*Contribution to Project: Conducted experiments and knee angle data analysis to reduce crosstalk-induced errors.*
*Funding Support: Also funded by the W.M. Keck Foundation.*

*Name: Greg Orekhov*
*Project Role: Undergraduate Student*
*Nearest person month worked: 8*
*Contribution to Project: Purchased and installed equipment. Developed protocols for conducted EMG-driven inverse dynamic analyses. Conducted experiments and data analysis of ground/pedal reaction forces, knee angles, and knee joint loads.*
*Funding Support: Also funded by the W.M. Keck Foundation.*

*Name: Michael Rumery*
*Project Role: Graduate Student*
*Nearest person month worked: 9*
*Contribution to Project: Developed finite element models and analyses to determine cartilage tissue loading.*

*Name: Greg Lane*
*Project Role: Undergraduate Student*
*Nearest person month worked: 7*
*Contribution to Project: Developed finite element models and analyses to determine cartilage tissue loading.*
*Funding Support: Also funded by the W.M. Keck Foundation.*

*Name: Samuel Tucker*
*Project Role: Undergraduate Student*
*Nearest person month worked: 6*
*Contribution to Project: Conducted experiments and knee angle data analysis using PRB method to reduce soft tissue artifact-induced errors.*
*Funding Support: Also funded by Cal Poly's Human Motion Biomechanics Lab account (accrued with gifts/donations) and the W.M. Keck Foundation.*

*Name: Elizabeth Heyde*

*Project Role: Undergraduate Student*
*Nearest person month worked: 1*
*Contribution to Project: Conducted experiments and data analysis of ground/pedal reaction forces, knee angles, and knee joint loads.*
*Funding Support: Also funded by the W.M. Keck Foundation.*

*Name: Jonathon Stearns*
*Project Role: Undergraduate Student*
*Nearest person month worked: 1*
*Contribution to Project: Conducted experiments and data analysis.*
*Funding Support: Also funded by the W.M. Keck Foundation.*

*Name: Emily Hubbard*
*Project Role: Undergraduate Student*
*Nearest person month worked: 1*
*Contribution to Project: Conducted experiments and data analysis.*
*Funding Support: Also funded by the W.M. Keck Foundation.*

*Name: Emily Vassilev*
*Project Role: Undergraduate Student*
*Nearest person month worked: 1*
*Contribution to Project: Conducted experiments and data analysis.*
*Funding Support: Also funded by the W.M. Keck Foundation.*

*Name*: *Megan Pottinger*
*Project Role: Undergraduate Student*
*Nearest person month worked: 4*
*Contribution to Project: Conducted experiments and data analysis to determine knee joint loads.*
*Funding Support: Also funded by the W.M. Keck Foundation.*

*Name*: *Katherine Mavrommati*
*Project Role: Undergraduate Student*
*Nearest person month worked: 4*
*Contribution to Project: Conducted experiments and data analysis to determine knee joint loads.*
*Funding Support: Also funded by the W.M. Keck Foundation.*

*Name: Nina Yadlowsky*
*Project Role: Undergraduate student*
*Nearest person month worked: 4*
*Contribution to Project: Conducted experiments and knee angle data analysis using PRB method to reduce soft tissue artifact-induced errors.*

*Name: Alejandro Gonzalez-Smith*
*Project Role: Graduate student*

*Nearest person month worked:* *5*
*Contribution to Project:* *Conducted experiments and knee angle data analysis using PRB method to reduce soft tissue artifact-induced errors.*

**Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?**
Nothing to report.

**What other organizations were involved as partners?**
Nothing to report.

## 8. SPECIAL REPORTING REQUIREMENTS

Nothing to report.

## 9. APPENDIX

*Bibliography*

[1] S. Tucker, N. Yadlowsky, V. Profiti, S.J. Hazelwood, S.M. Klisch, A pseudo-rigid body method for soft tissue artifact (STA): results for STA simulation and standard gait experiments, in: Annu. Meet. Biomed. Eng. Soc., 2017.

[2] S. Tucker, V. Profiti, S.J. Hazelwood, S.M. Klisch, Knee angles with soft tissue artifact correction for normal weight and overweight subjects in gait and cycling, in: World Congr. Biomech., 2018.

[3] J.D. Gutierrez-Franco, J.M. Skaro, S.J. Hazelwood, S.M. Klisch, Knee biomechanics during cycling are similar for normal weight and obese subjects, in: Summer Biomech. Bioeng. Biotransport Conf., 2017.

[4] J.M. Skaro, H. Goel, S.J. Hazelwood, S.M. Klisch, Principal component analysis of gait and cycling experiments: crosstalk error reduction and corrected knee axes, in: Summer Biomech. Bioeng. Biotransport Conf., 2017.

[5] G. Orekhov, E.A. Heyde, A.M. Robinson, S.J. Hazelwood, S.M. Klisch, Ground/pedal reaction forces and knee flexion angles for transtibial amputees in gait and cycling, in: Annu. Meet. Biomed. Eng. Soc., 2017.

[6] G. Orekhov, E.A. Heyde, A.M. Robinson, S.J. Hazelwood, S.M. Klisch, Asymmetry in peak ground/pedal reaction forces for transtibial amputees in gait, cycling, and elliptical training, in: World Congr. Biomech., 2018.

[7] M. V. Pottinger, K. Mavrommati, S.J. Hazelwood, S.M. Klisch, EMG-driven inverse dynamic analysis of knee contact forces during gait and cycling using OpenSim, in: Summer Biomech. Bioeng. Biotransport Conf., 2017.

[8] G.T. Lane, M.G. Rumery, S.M. Klisch, S.J. Hazelwood, Human knee FEA model for transtibial amputee tibial cartilage pressure in gait and cycling, in: World Congr. Biomech., 2018.

[9] M.G. Rumery, G.T. Lane, S.M. Klisch, S.J. Hazelwood, Finite element analysis predictions of knee cartilage contact pressure in gait and dependence on material model choice, in: World Congr. Biomech., 2018.

These papers corresponding to references [2,4–9] (in that order) are included in the remaining pages of this Appendix.

# KNEE ANGLES WITH SOFT TISSUE ARTIFACT CORRECTION FOR NORMAL WEIGHT AND OVERWEIGHT SUBJECTS IN GAIT AND CYCLING

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## Introduction

One risk factor for knee osteoarthritis (OA) is obesity [1]. Previous studies have measured knee angles for normal weight (NW) and obese (OB) but not overweight (OW) subjects in gait, e.g. see [2]. Those studies have not considered other exercises nor corrected for soft tissue artifact (STA), which is a primary source of error using skin-based marker systems. This study used two analytical methods to correct for STA: pseudo-rigid body (PRB) [3] and Procrustes solution (PS) [4] methods. The hypothesis was that knee angles will differ in gait but not in cycling between NW and OW subjects.

## Methods

Six healthy NW (BMI = 21.8±2.5) and OW (BMI = 27.8±1.4) subjects aged 18-25 participated. Kinematic data was collected using a motion analysis system (Motion Analysis Corp., Santa Rosa, CA, USA). Five gait trials at self-selected speeds were conducted using 3 ground force plates (AMTI, Watertown, MA, USA). Three trials at 70 RPM and moderate machine resistance levels were conducted using a stationary bike. Clusters of 7 markers were used to obtain STA corrected body segment orientations.

A floating axis coordinate system [5] was used to define knee angles: flexion/extension (FE), internal/external (IE) rotation, and adduction/abduction (AA). Custom codes (Matlab, Natick, MA, USA) were used to perform PRB and PS analyses. Significant differences between NW and OW subjects were determined by independent two sample t-tests ($p < 0.05$).

## Results

There existed significant differences between NW and OW maximum IE and AA angles in gait (Fig. 1) with both PRB and PS methods, with OW subjects displaying external rotation and adduction offsets.

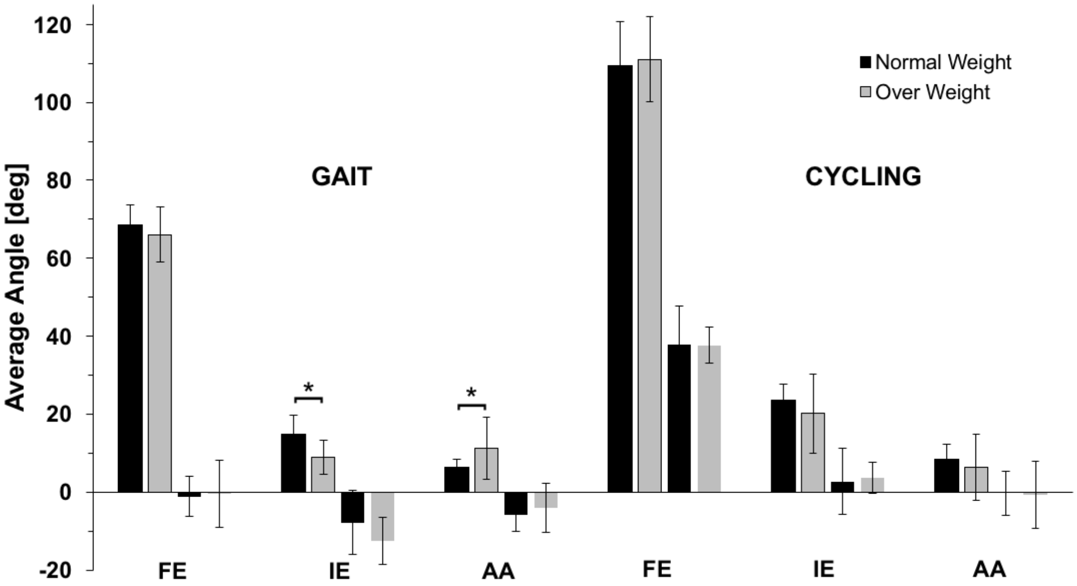

Figure 1. PRB predicted maximum/minimum FE, IE, and AA angles in gait and cycling averaged over all NW and OW subjects (n=6 each). Mean ±1 S.D. shown. * indicates significance.

## Discussion

NW and OW knee kinematics differed in gait but not in cycling. In gait, observed trends in OW subjects were similar to those found in OB subjects [2] and suggests that OA risk due to excess body weight may increase before BMI reaches obese status. In [6], ACL deficient subjects displayed an IE offset, which was hypothesized to be linked to high OA risk. We observed an offset in the opposite direction (external rotation) that may also be linked to high OA risk.

## Acknowledgments

Supported by the Defense Health Program through the Department of Defense under Award No. W81XWH-16-1-0051, W.M. Keck Foundation.

## References

[1] Issa, et al., *Opnion Rheumatology,* 18:147-56, 2006.
[2] Lerner, AL. et al., *J Pediatr Orthop*, 25:763-8, 2005.
[3] Solav, D. et al., *Int J Eng Sci*, 85:1-9, 2015b.
[4] Söderkvist, I. et al., *J biomech*, 26:1473-1477, 1993.
[5] Wu-Cavanaugh, *J biomech*, 10: 1257-1261, 1995
[6] Andriacchi et al., *J Ortho Resrch* 22: 794-800, 2004.

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# PRINCIPAL COMPONENT ANALYSIS OF GAIT AND CYCLING EXPERIMENTS: CROSSTALK ERROR REDUCTION AND CORRECTED KNEE AXES

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## INTRODUCTION

Crosstalk is a leading source of error in motion analysis [1-2]. Due to incorrect flexion axis direction that develops from marker placement error, crosstalk results in a strong, anatomically incorrect correlation between flexion-extension (FE) and adduction-abduction (AA) motions [1-2]. Thus, crosstalk limits the ability of biomechanical models to reflect the “true” motion of the knee. Principal Component Analysis (PCA) has been proposed as a post-hoc correction for crosstalk in prior gait studies [1-2]; however, previous studies have not proposed a method to determine PCA corrected knee axes. Further, it is not clear how PCA should be implemented in motion analysis studies that involve several exercises, on the same subjects, involving a relatively high range of flexion angles.

The long-term goal of this study is to determine accurate knee kinematics in a variety of exercises performed by the same subjects. This study tests two hypotheses: (1) PCA corrects for crosstalk between FE and AA angles in gait and cycling and (2) PCA corrected knee axes are similar for gait and cycling. The aims are to (1) determine PCA corrected knee angles in gait and cycling for the same subjects and their corresponding FE-AA correlations, (2) develop and implement an algorithm for determining PCA corrected knee FE and AA axes, and (3) compare the PCA corrected FE and AA axes for the same subjects to determine if they are similar in gait and cycling.

## METHODS

**Subject Selection**. Subjects were male (n=5) and female (n=1), 21-26 years of age, and non-obese. Subjects were screened for prior leg injuries or malalignment that could bias results. Subjects 1, 2, 4 and 5 were right leg dominant while subjects 3 and 6 were left leg dominant. Protocols were approved by Cal Poly’s Human Subjects Committee to minimize risk to human subjects.

**Experimental Procedure**. An enhanced Helen Hayes marker set with retroreflective markers was used to determine kinematics. A ten-camera motion capture system and Cortex software (Motion Analysis, Santa Rosa, CA, USA) were used to record marker position and process kinematic data. Subjects stood motionless for a static trial to create virtual axes for body segments. Subjects walked across the load cell walkway leading with their dominant leg to capture a full gait cycle. Subjects then pedaled a stationary bicycle (LifeFitness LifeCycle GX, Rosemont, IL, USA) at 70 rpm for 15 seconds.

**PCA Analysis.** PCA was implemented to reduce crosstalk by conducting a coordinate system transformation of calculated knee angles that minimizes FE-AA correlations [3]. A covariance matrix $[\boldsymbol{S}]$ of the knee angle data was calculated as

$$[\boldsymbol{S}] = \frac{\boldsymbol{1}}{\boldsymbol{n-1}}[\boldsymbol{X_{centered}}]^{\boldsymbol{T}}[\boldsymbol{X_{centered}}] \tag{1}$$

where $[\boldsymbol{X_{centered}}]$ is the original knee angles, $[\boldsymbol{X}]$, with the means of each knee angle subtracted. An eigendecomposition of matrix $[\boldsymbol{S}]$ was calculated to produce a matrix of column eigenvectors, $[\boldsymbol{P}]$, according to

$$[\boldsymbol{S}] = [\boldsymbol{P}]^{\boldsymbol{T}}[\boldsymbol{X}][\boldsymbol{P}]. \tag{2}$$

Finally, the original knee angles, $[\boldsymbol{X}]$, were projected onto a new set of axes, as described by the eigenvectors in matrix $[\boldsymbol{P}]$. This results in the calculation of an *nx3* matrix $[\boldsymbol{Z}]$ which contains PCA corrected FE, internal-external rotation (IR), and AA angles:

$$[\boldsymbol{Z}] = [\boldsymbol{X}][\boldsymbol{P}]. \tag{3}$$

The coefficient of determination ($R^2$) between FE and AA angles was used to quantify crosstalk both before and after PCA. Larger $R^2$ values indicate the presence of more crosstalk.

**Calculating PCA Corrected Knee Axes.** PCA corrected knee axes were determined by finding the axes that, when used with PCA corrected knee angles, resulted in thigh, shank and ankle positions that

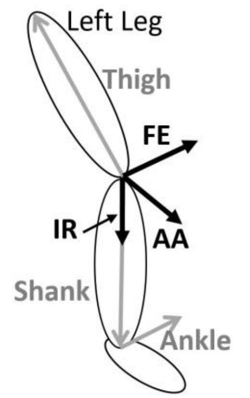

Fig. 1. Axis (FE, IR, AA) and body (Thigh, Shank, Ankle) vectors used in analysis.

were most similar to the corresponding positions determined by Cortex (which used the experimental marker data). A floating axis (i.e. AA axis) coordinate system was used [4]. In a local coordinate system, different for left and right leg dominant subjects, anterior and lateral directions were aligned with positive x- and y-directions, respectively, and inferior directions were defined as positive and negative for left and right leg dominant subjects, respectively (Fig. 1).

**Statistics.** Regression analyses were performed on FE vs. AA angles pre- and post-PCA treatment to assess FE-AA correlations in gait and cycling. Spherical directional statistics (i.e. Watson-Williams tests) [5-6] were used to assess for significant differences in the directions of the PCA corrected FE and AA axes between gait and cycling across all subjects. A one sample t-test was performed on the calculated angles between the corrected FE axes for gait and cycling to test if these angles were statistically similar to zero. For all statistical analysis tests, $p<0.05$ denotes statistical significance.

## RESULTS

$R^2$ correlation values (Table 1) between FE and AA knee angles (Fig. 2) were reduced by 3 and 4 orders of magnitude for gait and cycling, respectively. Regression analyses found reduced correlations for gait FE-AA knee angles ($p=0.000$ for pre-PCA [strongly correlated] and $p=0.857$ for post-PCA [not correlated]) and for cycling FE-AA knee angles ($p = 0.000$ for pre-PCA and $p=0.956$ for post-PCA). The spherical directional statistical tests found FE (Table 2) and AA (Table 3) axes to be similar among subjects for gait and cycling ($p=0.289$ for FE and $p=0.259$ for AA). The one sample t-test on the angles between the corrected FE axis for gait and cycling showed significant differences from zero ($p=0.022$).

**Table 1: $R^2$ values (mean ± 1 standard deviation) for FE-AA angles pre- and post-PCA correction for gait and cycling.**

| | Gait | Cycling |
|---|---|---|
| Pre | .66 ± .28 | .21 ± .28 |
| Post | 2.5E-04 ± 2.7E-04 | 6.7E-05 ± 1.5E-04 |

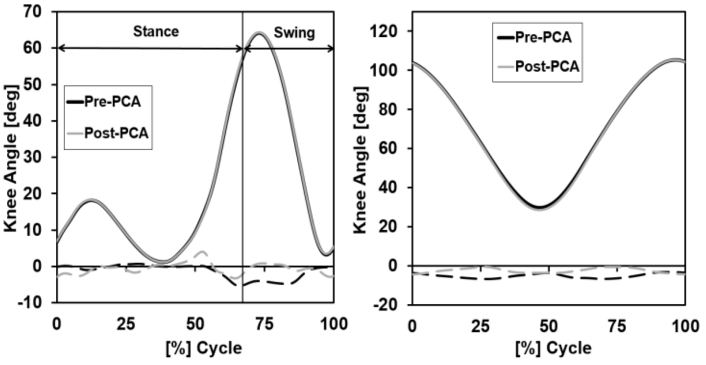

**Fig 2: FE and AA knee angles pre- and post-PCA correction for gait and cycling for one subject. Solid/dashed lines = FE/AA.**

**Table 2: PCA corrected FE axes (in [x,y,z] format) and angle between axes (in degrees) for gait and cycling.**

| Subject | Gait | Cycling | Angle |
|---|---|---|---|
| 1 | [0.28,0.96,0] | [0,1,0] | 16 |
| 2 | [0.28,0.96,0] | [0.31,0.95,0] | 2 |
| 3 | [0.10,0.99,0] | [0.62,0.79,0] | 32 |
| 4 | [0.28,0.96,0] | [0.10,0.99,0] | 10 |
| 5 | [0.50,0.87,0] | [0.10,0.99,0] | 24 |
| 6 | [-0.17,0.98,0] | [0.62,0.79,0] | 48 |

**Table 3: PCA corrected AA axes (in [x,y,z] format) and angle between axes (in degrees) for gait and cycling.**

| Subject | Gait | Cycling | Angle |
|---|---|---|---|
| 1 | [0.96,-0.28,0.02] | [1.00,0,0.02] | 16 |
| 2 | [0.95,-0.27,-0.04] | [0.94,-0.31,-0.04] | 2 |
| 3 | [0.99,-0.10,0.08] | [0.79,-0.61,0.07] | 32 |
| 4 | [0.96,-0.27,0.05] | [0.99,-0.10,0.05] | 10 |
| 5 | [0.86,-0.50,-0.05] | [0.99,-0.10,-0.03] | 24 |
| 6 | [0.97,0.17,-0.13] | [0.78,-0.61,-0.05] | 48 |

## DISCUSSION

The statistical analyses demonstrated that there is substantial crosstalk between knee axes for gait and that PCA can correct for it. It is unsure if the corrected knee axes are similar between gait and cycling due to the large angles between corrected and uncorrected FE and AA axes. Similarities between those axes were found using the spherical statistical analysis while the one sample t-test indicates the FE axis between gait and cycling may be different. However, the spherical statistical test may find significant differences with more subjects. Other studies reported that a correlation exists between FE and AA angles at high flexion angles (> 60 deg.) [7]; thus, the predicted knee axes may be incorrect for cycling due to the high flexion angles measured in cycling (maximum flexion angles were 106 deg. in cycling and 62 deg. in gait). Thus, when using PCA to correct for crosstalk error in subjects performing exercises with high-flexion motions, these results suggest that PCA corrected axes from gait analysis may be used as a standard set of knee axes for other motions.

This study has several limitations. First, the number of subjects was relatively low; inclusion of additional subjects may lead to detected differences in the corrected knee axes for gait and cycling using the spherical directional statistics test. Second, methods were not used to reduce errors induced by soft tissue artifact, which is considered another leading source of error in motion analysis. Despite these limitations, this study has shown that PCA can be used to correct for crosstalk in both gait and cycling experiments and may be used to motivate further studies to determine the optimal method for reducing crosstalk when analyzing knee motion for subjects performing multiple exercises or high-flexion motions.

## ACKNOWLEDGEMENTS

This work was supported by the Donald E. Bently Center (SK), W.M. Keck Foundation (JS), and the Defense Health Program (JS, SH, SK) through the Department of Defense Broad Agency Announcement for Extramural Medical Research Program #W81XWH-BAA-14-1 under Award No. W81XWH-16-1-0051. Opinions, interpretations, conclusions and recommendations are those of the authors.

## REFERENCES

[1] Baudet, A. et al,. *PLOS ONE*,, 9:1-7, 2014. [2] Jensen, E. et al., *J Biomech*, 49:1698-1704, 2016. [3] Shlens, J., *arXiv*:1404.1100, 2014. [4] E. S. Grood et al., *J Biomech*, 105:136-144, 1983. [5] Watson, G. S et al., *Biometrika*, 43:344-52, 1956. [6] Watson, G. S et al., *Geophysical J International*, 7:153-59, 1956. [7] D. R. Wilson et al., *J Biomech*, 33:465-473, 2000.

# Ground/Pedal Reaction Forces and Knee Flexion Angles for Transtibial Amputees in Gait and Cycling

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**Introduction:** Abnormal biomechanics is a risk factor for knee osteoarthritis (OA) [1] and is likely related to high risk of contralateral (intact) knee OA for transtibial (TT) amputees [2]. In gait, ground reaction force (GRF) asymmetries exist for TT amputees that depend on prosthetic design [3]. In cycling, pedal reaction force (PRF) and work asymmetries exist for TT amputees that depend on cycling intensity and prosthetic stiffness [4]. However, there does not exist a study of gait and cycling biomechanics for the same TT amputee group. Further, pedal shear forces in cycling for TT amputees have not been investigated. Our long-term goal is to assess OA risk in select exercises for TT amputees. The objective of this study was to conduct motion analysis studies and compare GRFs and PRFs and dominant leg knee flexion angles for TT amputee and control subjects.

**Materials and Methods:** Protocols were approved by Cal Poly's Human Subjects Committee. Kinematic data were collected using a camera motion analysis system with Cortex software (Motion Analysis Corp., Santa Rosa, CA, USA). 5 gait trials at self-selected speeds were conducted using 3 ground force plates (Accugait, AMTI, Watertown, MA, USA). 3 cycling trials at 70 RPM and moderate machine resistance level (10) were conducted using a stationary bike (Lifecycle GX, Life Fitness, Schiller Park, IL, USA) retrofitted with custom pedals with 6-axis load cells (AD2.5D, AMTI, Watertown, MA, USA). TT amputee (3 male, age 31-45, 3-13 years post-op) and control (5 male, 1 female, age 21-29) subjects were tested. An enhanced Helen Hayes marker set with 32 markers was used to track kinematics. OpenSim (Stanford University, Palo Alto, CA, USA) analyses [5] were run using Inverse Kinematics and Residual Reduction Algorithm (RRA) tools. GRFs/PRFs (anterior/posterior (AP) shear, medial/lateral (ML) shear, axial compression (AX)) normalized by body weight (BW) and RRA-corrected knee flexion (F) ranges were averaged across subject groups for each exercise. Two-factor ANOVAs (subject group and exercise type) were performed to compare maximum and minimum values ($p<0.05$ significant). A post-hoc Tukey test at 95% confidence was used to identify statistically significant results.

**Results and Discussion:** Maximum and minimum AP, maximum ML, and maximum AX loads were higher in gait than cycling ($p<0.001$) regardless of subject group (Fig. 1). Maximum AP shear was higher in gait ($p<0.002$) for TT amputees than controls. Minimum AP and ML shear was lower ($p<0.01$) and higher ($p<0.001$), respectively, for TT amputees in cycling than controls. Knee flexion range in cycling was higher than gait ($p<0.001$) regardless of subject group. Flexion range was higher for TT amputees in cycling ($p<0.001$) but lower in gait ($p<0.001$) than controls.

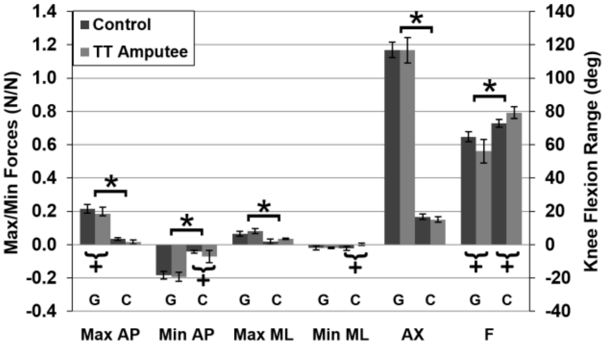


**Fig 1.** Mean ±1 S.D. maximum/minimum forces normalized by BW and flexion ranges for gait (G) and cycling (C). Anterior, medial, axial forces are positive. */+=significant difference across exercise/subject group.

**Conclusions:** The results reinforce that cycling may be a preferred exercise for rehabilitation and limiting OA risk for TT amputees due to lower vertical and shear loads as compared to gait. Differences in knee flexion range for both exercises suggest that a compensation mechanism is in effect that could be partially responsible (among other factors such as knee flexor/extensor activity) for the increased risk of knee OA in TT amputees. Further investigation of TT amputee biomechanics may include EMG-driven OpenSim Inverse Dynamics analyses to determine knee contact loads in different exercises for TT amputees. A limitation to this study was sample size.

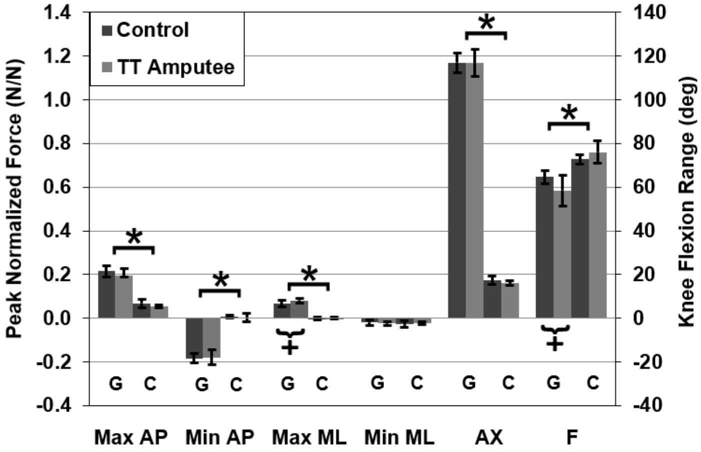
**Acknowledgements:** Donald E. Bently Center (SK) and Defense Health Program (GO, EH, SH, SK) through the Department of Defense Broad Agency Announcement for Extramural Medical Research Program #W81XWH-BAA-14-1 under Award No. W81XWH-16-1-0051. Opinions, interpretations, conclusions and recommendations are those of the authors.

**References:** [1] Andriacchi TP et al., *Curr Opin Rheumatol*, 18: 514-18, 2006. [2] Ebrahimzadeh MH et al., *Mil Med*, 174: 593-7, 2009. [3] Snyder RD et al., *J Reha. Res Dev*, 30: 309-15, 1995. [4] Gailey RS et al., *Care of the Combat Amputee, TMM*, 451-92, 2009. [5] Delp LS et al. *IEEE Trans Biomed Eng*, 54:1940-50, 2007.

## Addendum 2017 November 15

**Materials and Methods:** One additional male amputee subject was tested (total 4 male, age 31-45, 3-13 years post-op) and updated results were presented at the 2017 BMES conference in Phoenix, Arizona.

**Results and Discussion:** Adding one amputee subject to the study changed some of the results. Maximum anterior, posterior, medial, and axial forces were higher in gait than cycling for all subjects ($p<0.001$). Maximum medial shear was higher in gait for TT amputees than controls ($p<0.02$). Knee flexion range in cycling was higher than gait ($p<0.001$) across all subjects. Knee flexion range was lower for TT amputees in gait ($p<0.001$) than controls. No significant differences were found in cycling between TT amputees and controls.



**Revised Fig. 1:** Mean ±1 S.D. maximum/minimum forces normalized by BW and flexion ranges for gait (G) and cycling (C). Anterior, medial, axial forces are positive. ***/+**=significant difference across exercise/subject group.

**Conclusion:** The results reinforce that cycling may be a preferred exercise for rehabilitation and limiting OA risk for TT amputees due to lower vertical and shear loads as compared to gait. Differences in knee flexion range in gait suggest that a compensation mechanism is in effect that could be partially responsible (among other factors such as knee flexor/extensor activity) for the increased risk of knee OA in TT amputees. No significant differences in axial and shear reaction forces and knee flexion range in cycling were found between TT amputees and controls suggesting that constrained exercises may reduce biomechanical differences between subject groups. Further investigation of TT amputee biomechanics may include EMG-driven OpenSim Inverse Dynamics analyses to determine knee contact loads in different exercises for TT amputees. A limitation to this study was sample size.

# Asymmetry in Peak Ground/Pedal Reaction Forces for Transtibial Amputees in Gait, Cycling, and Elliptical Training

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## Introduction

Abnormal biomechanics is likely related to high risk of contralateral (intact) knee OA for transtibial (TT) amputees [1,2]. Biomechanical challenges exist for TT amputees in gait [3] and cycling [4] that depend on intensity and prosthetic design. There do not exist any studies of pedal reaction forces (PRFs) during elliptical training for TT amputees for gait, cycling, and elliptical training biomechanics for the same TT amputee group. This study's hypotheses are that, at peak axial load, the magnitude of reaction forces will depend on subject (TT amputee, controls), exercise type (gait, cycling, elliptical) and leg (dominant, contralateral).

## Methods

Protocols were approved by Cal Poly's Human Subjects Committee. Kinematic data with an enhanced Helen Hayes markerset were collected using a motion analysis system (Motion Analysis Corp., Santa Rosa, CA, USA). Five gait trials at self-selected speeds were conducted using 4 ground force plates (AMTI, Watertown, MA, USA). Three trials at 70 RPM and moderate machine resistance levels were conducted using a stationary bike and elliptical trainer, each retrofitted with AMTI pedal load cells. TT amputee (5 M, 1 F, age 31-45) and control (5 M, 1 F, age 21-29) subjects participated. Ground reaction forces (GRFs) and PRFs (anterior/posterior (AP) shear, medial/lateral (ML) shear, axial compression (AX)) were normalized by body weight. ML and AP shears were combined into total shear (TS) at the time of peak AX load. Two-factor ANOVAs with repeated measures were performed ($p<0.05$ significant; post-hoc Tukey test at 95% confidence).

## Results

There were significant differences between dominant and non-dominant AX and TS loads in gait ($p<0.001$) for TT amputees (Fig. 1). AX loads in elliptical ($p<0.001$) were significantly different between TT amputees and controls regardless of leg.

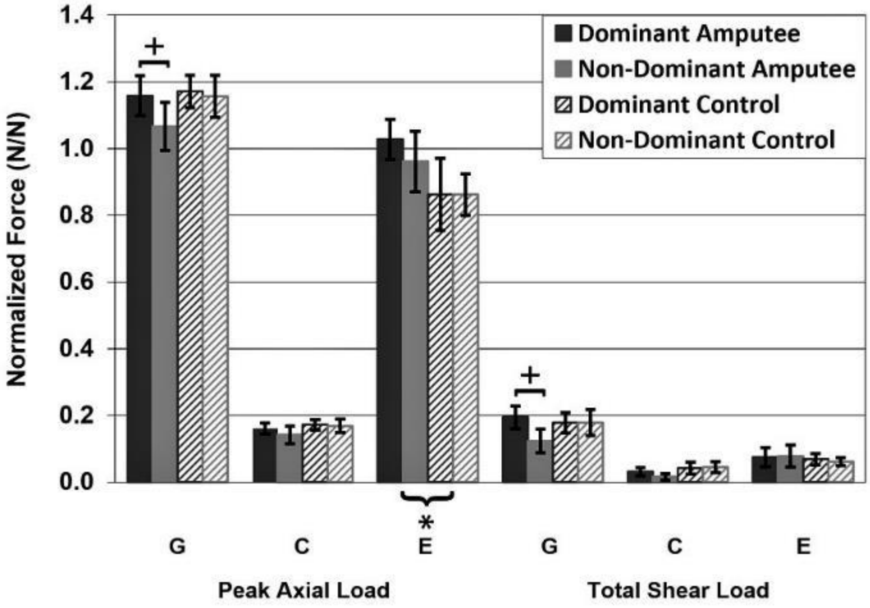

**Figure 1.** Mean ±1 S.D. dominant and non-dominant AX/TS loads for TT amputees and controls in gait (G), cycling (C), and elliptical training (E). */+ indicates significant differences across subject group and leg, respectively.

## Discussion

The results indicate that load asymmetries are present only in gait and that structured exercises that constrain user kinematics, such as cycling and elliptical training, can reduce asymmetry for TT amputees. Elliptical training reduced asymmetry in TT amputees but AX loads were higher compared to controls. Cycling may be a preferred exercise because of relatively low AX and TS loads.

## Acknowledgements

Supported by the Defense Health Program through the Department of Defense under Award No. W81XWH-16-1-0051 and Cal Poly's Donald E. Bentley Center.

## References

[1] Andriacchi, T.P., et al., (2006). *Curr Opin Rheumatol*, **18**(5) p514
[2] Ebrahimzadeh, M.H., et al., (2009). *Mil Med*, **174**(6) p593
[3] Snyder, R.D., et al., (1995). *J Rehabil Res Dev*, **32** p309
[4] Gailey, R., et al., (2009). *Prosthet Orthot Int*, **33**(3) p242

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# EMG-DRIVEN INVERSE DYNAMIC ANALYSIS OF KNEE CONTACT FORCES DURING GAIT AND CYCLING USING OPENSIM

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## INTRODUCTION

Joint contact forces determine the loading experienced by cartilage tissue and, thus, may be used to predict risk of cartilage tissue damage and osteoarthritis (OA). Participating in low impact and/or non-weight bearing activities such as cycling may help reduce knee OA risk by limiting forces exerted during exercise [1]. Cycling is a common recommendation for rehabilitative or fitness sustainment exercise for select patients [1]. Although knee joint contact forces have been directly measured in gait and cycling using instrumented knee implants [2,3] and calculated in gait using EMG-driven analysis [4]; they have not been calculated in cycling using EMG-driven analysis.

The long-term goal of this study is to identify weight control exercises for overweight (OW) and obese (OB) subjects that minimize OA risk. This current study tests the hypothesis that knee joint contact forces are significantly lower during cycling than gait. The objectives are to: (1) conduct motion analysis experiments and EMG-driven OpenSim analyses for gait and cycling, (2) compare predicted tibiofemoral (TF) contact forces to published values, and (3) test for significant differences in maximum TF compressive forces in gait and cycling.

## METHODS

**Equipment.** Kinematic data was collected using a 10-camera motion analysis system with Cortex software (Motion Analysis Corp., Santa Rosa, CA, USA). Gait experiments were conducted using 3 ground force plates (Accugait, AMTI, Watertown, MA, USA). Cycling experiments used a stationary bike (Lifecycle GX, Life Fitness, Schiller Park, IL, USA) retrofitted with custom pedals containing 6-axis load cells (AMTI, Watertown, MA, USA). EMG data was collected using 4 wireless EMG sensors (Trigno, Delsys, Natick, MA, USA).

**Experimental Studies.** Six subjects (average body mass index (BMI) = 25.0) aged 18-26 years and with no previous knee injury history participated. Protocols were approved by Cal Poly's Human Subjects Committee and were designed to minimize risk to human subjects. EMG sensors were placed on the following dominant leg muscles: lateral gastrocnemius, vastus lateralis, vastus medialis and semimembranosus. An enhanced Helen Hayes marker set with 32 retroreflective markers was used to track kinematics. First, the subjects performed 10 gait trials, 5 analyzing each leg, at self-selected walking speeds. Subsequent analyses used the middle three trials of the dominant leg. Then, each subject performed 3 cycling trials at a moderate machine resistance level (10) and 70 RPM. A static trial was captured at the end of the experiments for determining reference knee angles and scaling procedures in OpenSim (Stanford University, Palo Alto, CA, USA). Finally, body mass, height and Q-angle measurements were recorded.

**Data Processing and Analysis.** Trials were processed using Cortex to identify markers and create virtual markers to generate vectors of body segments. Kinematic and kinetic data were filtered (4th order Butterworth filter, cutoff frequency = 6 Hz) and exported to Matlab (MathWorks, Natick, MA, USA). EMG data were also exported to Matlab and time synced with the kinematic data. A bandpass filter of 20Hz to 450Hz [5] was applied to the time synced EMG data to create a Control Constraints file for muscle activation input to OpenSim [4].

OpenSim analyses proceeded with the following steps. (1) A full body musculoskeletal model was scaled to each subject [6]. (2) The Inverse Kinematics (IK) and Residual Reduction Algorithm (RRA) tools were used to output joint kinetic data and a corrected kinematic file. (3) An EMG-driven Computed Muscle Control (CMC) analysis was used to obtain muscle activations. (4) CMC results were used in Joint Reaction (JR) analysis to calculate knee joint contact forces. Results were normalized by body weight (BW) and trimmed to one full gait cycle of the dominant leg (0% = 1st heel strike, 100% = 2nd heel strike), and one full crank revolution (0 deg. = 1st top dead center, 360 deg. = 2nd top dead center).

**Statistics.** A paired t-test was used to compare the knee joint compressive contact forces for the two types of exercises (gait vs. cycling). Significance levels were defined by $p = 0.05$.

## RESULTS

Results for TF compressive forces were more similar to publications for gait [4] than for cycling [2, 3]. For gait, average TF compressive contact forces (Fig. 1) closely resembled published results when subjects walked at 1.25 m/s [4]; the 6 subjects of this current study had an average walking speed of 1.32 m/s. For cycling, average TF compressive contact forces (Fig. 1) resembled published results [3], which reported knee forces during cycling at select power outputs. In particular, in [3] the reported maximum TF contact force at a power of 25 W was 0.6xBW, whereas in this study the maximum TF compressive contact force at an average power of 26 W was 0.75xBW. Also for cycling, our maximum TF contact forces were 27% lower compared to those reported in [2]. Peak compressive forces experienced during gait were 2.9xBW while for cycling they were 0.75xBW, a difference that was found to be significant (Fig. 2).

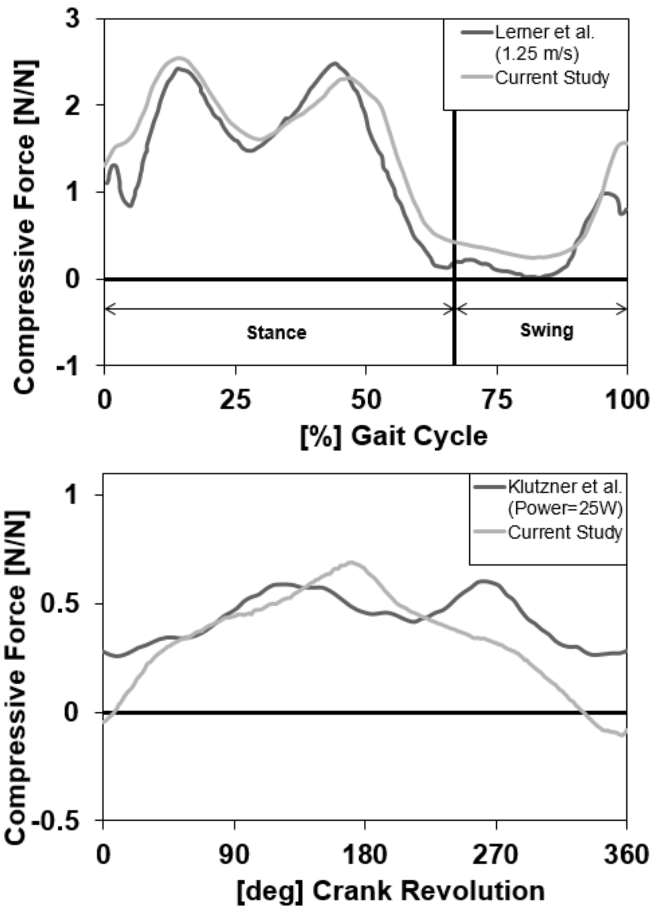

**Fig. 1: Tibiofemoral joint compressive contact forces normalized by BW and averaged over 6 subjects during one full gait cycle and one full crank revolution.**

## DISCUSSION

These findings reinforce the hypothesis that cycling results in relatively low TF joint compressive contact forces. A novel finding of this study is that OpenSim may be used to calculate knee contact forces during cycling as the results generally agreed with published results.

The difference in the graphs for compressive forces during cycling, observed in Fig. 1, might be due to the difference in setup of the subject on the stationary bike, the type of stationary bike, and the pedal design (i.e. clipped vs strapped). For this study, an upright stationary bike was used and the seat height was positioned such that at 180° crank angle the subject's leg was almost straight. It should be noted that the published results in Fig 1. were recorded at a cadence of 40rpm while our subjects kept a 70rpm constant cadence. Also, the subjects used in [4] were older and were suffering from OA.

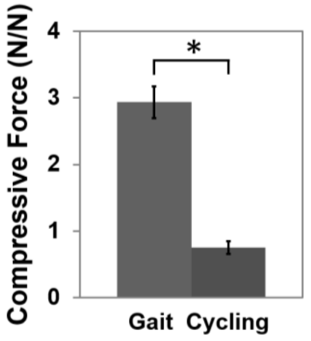

**Fig. 2: Maximum TF compressive force for gait and cycling (n=6). Mean ±1 S.D. shown. *Significant difference ($p<0.0001$).**

It is emphasized that in OpenSim's RRA, a pelvic residual is introduced for dynamic consistency. For gait, that pelvic residual is minimized to a value close to zero, but for cycling the pelvic residual is minimized to a relatively large value that should represent the effect of seat and handlebar forces. A future study should directly measure the seat and handlebar forces and, thus, provide an experimental target for the pelvic residual.

This study calculated TF joint contact forces for cycling and gait non-invasively using an EMG-driven inverse dynamics OpenSim analysis. The results suggest that cycling may be the preferred exercise for limiting OA risk in populations at high risk for knee OA. In order to better identify exercises that minimize the OA risk, future studies may include other potential weight control and fitness sustainment exercises and populations that are at high risk for knee OA such as obese, amputee, and ACL reconstructive surgery subjects.

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## REFERENCES

[1] McLeod, W et al., *Am J Sports Med*, 8:175-180, 1980.
[2] D'Lima, D et al., *Clin Orth Rel Res* 469:2953-2970, 2011.
[3] Kutzner, I et al., *J Orth Sports Phys Ther*. 42:1032–1038, 2012.
[4] Lerner, Z. F et al., *Gait & Posture.* 39:978–84, 2014.
[5] De Luca, C et al., *J Biomech*, 43:1573-1579, 2010.
[6] Anderson F et al., *J Biomech Eng*, 123:381-390, 2001.

# HUMAN KNEE FEA MODEL FOR TRANSTIBIAL AMPUTEE TIBIAL CARTILAGE PRESSURE IN GAIT AND CYCLING

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## INTRODUCTION

Transtibial amputees face high risk for osteoarthritis in their contralateral (intact) knee [1]. Current knowledge of osteoarthritis indicates that lower joint loads decrease risk for osteoarthritis due to lower cartilage contact pressure (CCP) [2]. Non-impact exercises like cycling are often recommended for at-risk patients, but a study comparing the effects of gait and cycling on tibial CCP for a transtibial amputee population has not been performed. In this knee finite element analysis (FEA), we hypothesized that tibial CCP depends on an individual's amputee status and exercise choice.

## METHODS

A healthy control subject received an MRI scan of their dominant knee. Tibiofemoral bones, cartilage, and menisci were segmented and meshed with 10 node tetrahedral elements, then imported into the FEA software ABAQUS (Dassault Systems, Providence, RI, USA) for analysis. Bones were modeled as rigid while cartilage and menisci were modeled as linearly elastic isotropic, due to the quasi-static nature of the analysis [3]. Ligaments were modeled as non-linear springs [4].

Model validity was assessed using experimental data for CCP [5]. Unpublished data from inverse dynamic analyses of gait and cycling experiments for three transtibial amputees and three controls were available for specifying model boundary conditions, creating six unique FEA models. Dominant (control) or contralateral (amputee) knee shear forces, moments, and flexion angles corresponding to the maximum compressive resultant force were applied. Two-way ANOVA determined tibial CCP differences due to amputee status and exercise type in the medial and lateral compartments, followed by Tukey pairwise comparisons when significant (defined by $p<0.05$).

## RESULTS

Tibial CCP was significantly different between gait and cycling in the lateral compartment only ($p=0.0005$), but interactions between exercise type and subject status were insignificant in the medial ($p=0.141$) and lateral ($p=0.304$) compartments. Pairwise comparisons indicated that control gait results in the lateral compartment were different than control ($p=0.006$) and amputee ($p=0.005$) cycling results.

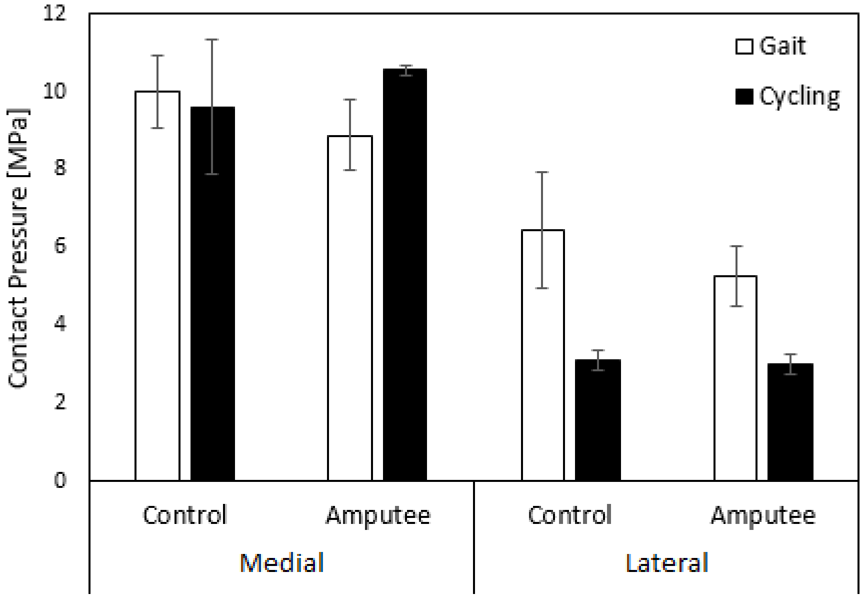

**Fig 1.** Tibial CCP results.

## DISCUSSION

Lower cycling tibial CCP in the lateral compartment is due to lower varus-valgus moments as measured experimentally, causing reduced loading in the lateral compartment while increasing it in the medial compartment. Results indicate that regardless of subject type, cycling exercises may help preserve the lateral tibial cartilage over gait exercises.

## ACKNOWLEDGEMENTS

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## REFERENCES

1. Ebrahimzadeh, M.H., et al., (2009). *Mil Med*, **174**(6) p593
2. Buckwalter, J.A., et al., (2013). *Cartilage*, **4**(4) p286
3. Yang, N.H., et al., (2010). *Comput Methods Biomech Biomed Engin*, **13**(5) p589
4. Blankevoort, L., et al., (1991). *J Biomech*, **24**(11) p1019
5. Seitz, A.M., et al., (2012). *J Orthop Res*, **30**(6) p934

# Finite Element Analysis Predictions of Knee Cartilage Contact Pressure in Gait and Dependence on Material Model Choice

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## Introduction

Cartilage material model choice affects finite element analysis (FEA) predictions of knee cartilage maximum principal stress [1] and contact pressure [2]. To the best of our knowledge, there does not exist a study of material model choice effects on cartilage contact pressure and area when using a subject-specific MRI-derived knee FEA model with subject-specific gait data. The objective of this study was to compare predicted cartilage contact pressures during gait for two elastic material model choices: Linear (LIN) and Neo-Hookean (NH).

## Methods

A subject-specific FEA mesh was created from a knee MRI scan with 45,000 and 11,000 quadratic tetrahedral hybrid elements for cartilage and menisci tissues, respectively. Material properties for LIN and NH models from [3,4] were selected to best match medial (M) and lateral (L) tibial cartilage maximum contact pressures in [5]. Unpublished data from inverse dynamic analysis of gait experiments were used to apply maximum compressive contact load and corresponding knee flexion/extension angle boundary conditions. Contact pressure and area in tibial and femoral cartilages were determined using a static analysis in Abaqus (SIMULIA, Providence, RI, USA).

## Results

For validation, LIN had 1% and -21% difference, and NH had 4% and -17% difference, respectively, compared to M and L tibial cartilage pressure from experiment [5]. During gait the maximum contact pressures on M and L tibial cartilages were 6% lower and 32% lower for NH, respectively, when compared to the LIN model. Contact area on M and L tibial cartilages were 44% higher and 36% higher for NH, respectively, when compared to the LIN model.

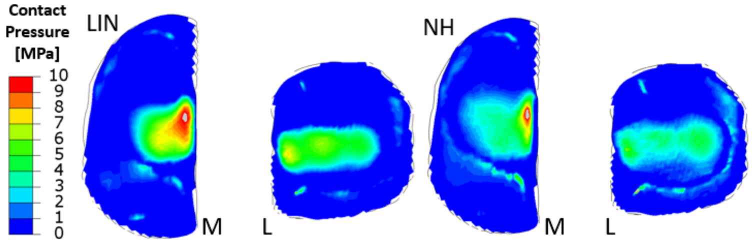

**Fig.1:** Tibial cartilage contact pressure during maximum gait loading. M=Medial, L=Lateral, LIN=Linear, NH=Neo-Hookean.

## Discussion

NH model predictions have lower contact pressure and higher contact area than LIN model due to the effects of nonlinear behavior at high loads. The in-vivo nature of this study limits subject-specific material testing, as the validation is performed using cadaveric specimens. Future studies will include multiple subjects, validation performed using multiple loads, and several exercise types with the goal of identifying preferred exercises for patients with high OA risk.

## Acknowledgments

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**References**

[1] Klets, O et al., (2016). *J. Biomech.*, **49**(16) p3891
[2] Mononen, M.E., et al., (2012). *J. Biomech.*, **45**(3) p579
[3] Pena, E. et al., (2006). *J. Biomech.*, **39**(9) p1686
[4] Henak, C.R. et al., (2014). *Biomech. Model. Mechanobiol.*, **13**(2) p387
[5] Seitz, A.M. et al., (2012). *J. Orthop. Res.*, **30**(6) p934