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AAO Foundation Final Report Form
(a/o 1/3/2018)

In an attempt to make things a little easier for the reviewer who will read this report, please consider these two questions before this is sent for review:

- *Is this an example of your very best work, in that it provides sufficient explanation and justification, and is something otherwise worthy of publication? (We do publish the Final Report on our website, so this does need to be complete and polished.)*
- *Does this Final Report provide the level of detail, etc. that you would expect, if you were the reviewer?*

Type of Award: Center Award

Name(s) of Principal Investigator(s)
Tracy Popowics
Dan Romanyk

Title of Project
Investigation of Periodontal Ligament Mechanics Under Orthodontic Tooth Loading: A Combined Experimental and Mechanical Modeling Approach

Period of AAOF Support
07-01-18 to 06-30-23

Amount of Funding
$75,000

Summary/Abstract

In the use of orthodontic treatment to correct tooth misalignments, the response of the periodontium to applied loads is of great interest. In particular, the induced stress-strain state within the periodontal ligament (PDL) is critical in that it drives the bone remodeling that allows for tooth movement during treatment. While this heightened stress-strain state is necessary to generate tooth movement, it is also critical that it not surpass an upper threshold where detrimental effects such as root resorption arise. Significant research exists in the literature towards the experimental and theoretical investigation of the PDL mechanical response to applied loading, yet a comprehensive program directly linking mechanics to stimulated biological effects remains elusive. The overarching focus of this Center Award is to develop a mechanobiology-focused Center between the University of Washington and University of Alberta whereby rigorous ex vivo and in vivo experimental methods are coupled with advanced modeling techniques to couple mechanical and biological responses of the periodontium under orthodontic loading.

In previous work completed at the University of Alberta, the use of in-fiber Bragg grating (FBG) sensors was demonstrated as a repeatable means to measure PDL strain ex vivo using a

swine model. While leading in the field, this work did not directly identify sensor location during testing. The first aim of this Center Award is to conduct similar ex vivo testing using a swine model at the University of Alberta and utilize high resolution microCT imaging methods to accurately locate the position of FBG sensors during testing. Furthermore, as a large volume of ex vivo testing will also be conducted at the University of Washington, a second miniature load frame that replicates the one used in Alberta will be constructed to remain in Washington. Ex vivo testing at the University of Alberta will focus on macroscopic mechanics of the periodontium, while the University of Washington will focus on linking specific mechanisms, namely fluid transfer and collagen fibers, to strain response measured by the FBG sensors.

Following ex vivo testing, research at the University of Alberta will move towards development of a finite element analysis (FEA) model based on collected microCT images. The developed model will be validated using both tooth crown force-displacement and PDL strain experimental data; a level of validation that has not yet been achieved in the literature. This model will be critical to the Center's future research in studying periodontium response, namely PDL, to applied loading and how this effects biological remodeling during tooth movement.

Finally, in vivo testing using a swine model will be conducted at the University of Washington to explore FBG sensor usage in live animals. This preliminary research will focus on demonstrating the repeatability of placing FBG sensors in vivo and studying the time at which PDL tissue disrupted by FBG sensor placement has regenerated and no longer exhibits differential response from baseline measurements. This will be the first time FBG sensors have been used in vivo to study PDL mechanics, and will be instrumental for the Center's future work in linking the mechanical and biological response of PDL tissue under applied loading.

The research proposed under this Center Award, and the future research that will stem from it, will significantly advance the literature in orthodontic biomechanics and mechanobiology. It will advance experimental methods both ex vivo and in vivo when studying PDL mechanics. The developed Center from this Award between the University of Washington and University of Alberta will combine proven expertise in PDL biology and biomechanics, respectively, in a unified approach to studying PDL mechanobiology. Significant advances in research from this Center will be vital to understanding optimum loads to be applied during orthodontic treatment which will influence both treatment and appliance design.

1. Were the original, specific aims of the proposal realized?

The original specific aims of this project included the following aims:

Year 1: In the first year of this AAOF Ormco Center Award our original specific aims were: i) to design and develop an *ex vivo* loading frame for the University of Washington and ii) to identify the location of Fiber Bragg sensor measurements within periodontal tissues using MicroCT imaging. These specific aims were completed and additional experiments evaluated how the orientation of the tooth-PDL-bone complex with respect to force application (i.e. loading vector) influenced subsequent strain measures. We utilized microCT methods to visualize sensor placement in three dimensions.

Year 2: In the second year of this award our specific aims were i) to identify the relative contributions of the fluid and fibrous components of the ligament to sensor measurements and ii) to develop an accurate swine-based FEA model for prediction of stresses and strains throughout the PDL space. These specific aims were completed, however, the Covid 19 pandemic delayed the time schedule for experiments. Our investigation of the relative contributions of the fluid and fibrous components of the ligament to sensor measurements was completed and an accurate swine-based FEA model was generated to predict stresses and strains throughout the PDL space.

Year 3: In the third year of this award our specific aim was to determine the repeatability of in vivo FBG sensor measurements in the PDL at different time points, and to assess the effects of repeated FBG placement on strain measurements over time. This aim was also completed, however, the time scale for experiments was delayed due to the Covid 19 pandemic.

2.
a. The results of these experiments have been published.

- Houg, K.P., Armijo, L., Doschak, M.R., Major, P.W., Popowics, T., Dennison, C.R., Romanyk, D.L., 2021. Experimental repeatability, sensitivity, and reproducibility of force and strain measurements from within the periodontal ligament space during ex vivo swine tooth loading. J. Mech. Behav. Biomed. Mater. 20, 104562. DOI: 10.1016/j.jmbbm.2021.104562.
- Houg, K.P., Camarillo, A.M., Doschak, M.R., Major, P.W., Popowics, T., Dennison, C.R., Romanyk, D.L., 2022. Strain measurement within an intact swine periodontal ligament. J. Dent. Res., 101(12):1474-1480. DOI: 10.1177/00220345221100234.
- Armijo, L., Mancl, L., Dennison, C.R., Houg, K. Romanyk, D., Popowics, T. (2023) In-fiber Bragg sensor measurements assess fluid effects on strain in the periodontal space of an ex-vivo swine incisor complex under mechanical loading, J. Biomech. 111729, ISSN 0021-9290, https://doi.org/10.1016/j.jbiomech.2023.111729.

b. AAOF support was acknowledged in each of these publications.
c. The results of the in vivo swine experiments have not yet been published, however, a manuscript is currently under preparation.

3. The results of this proposal have been presented and AAOF support was acknowledged.

- Hwang, I., Armijo, L., Mancl, L., Houg, K., Romanyk, D. and Popowics, T. Effect of PDL Fiberotomy/Collagenase on Mechanics During in-Vitro Loading. 2021 IADR/AADR/CADR General Session, Washington, D.C.(Virtual Experience), J. Dent. Res. 100 (Spec. Iss. A): ID 0352.

- Houg, K.P., Matos, A., Doschak, M.R., Popowics, T., Dennison, C. and Romanyk, D. Using In-Fibre Bragg Grating Sensors within the Periodontal Ligament Space of an Intact Swine Premolar: A Cross-Verification with a Representative Finite Element Model. XXVIII Congress of the International Society of Biomechanics (ISB) Digital Congress 25-29 July, 2021**.**

- Lu, J., Greenlee, G., Rafferty, K., Mancl, L., Romanyk, D.L., Popowics, T. *Ex vivo* strain measurement during incisor tipping force application. 2022 AADOCR Annual Meeting and Exhibition (Virtual Experience) Atlanta, Georgia.

- Hwang, I. Nguyen, Sample, M., Sangster, A., Romanyk, D., Rafferty, K., Greenlee, G., Popowics, T. Fiberoptic Sensors Measure Pig (*Sus scrofa*) PDL Strain *In Vivo.* 2023 AADOCR/CADR Annual Meeting & Exhibition. Portland, OR. Final Presentation ID: 0451.

4. To what extent have you used, or how do you intend to use, AAOF funding to further your career?

The development of expertise in the use of fiber optic sensors to measure periodontal ligament strain has provided a novel means of understanding the mechanobiology of the periodontium. This research has enriched my career through the development of new collaborations and opportunities to discuss periodontal mechanobiology at the national and international level. The results of this AAOF funded work to study fiber optic strain measurements in a swine model has also led to the acquisition of new funding to study strain in a primate model. The resulting publications from this AAOF award and the new funding are important to the advancement of my academic career.