

WORKSHOP
In Vivo Bone and Joint Loading –
How and Why Should We Measure It?

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In vivo bone and joint loading - how and why should we measure it?

Workshop Presented at the 2018 Annual Meeting of the Orthopaedic Research Society

1. Computational modeling approaches to estimate in vivo bone strain

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Bone strain and joint contact forces are key predictors of injury and disease progression. Accurate tissue loading values are also necessary for the development of engineered musculoskeletal tissue substitutes, such as cartilage and ligaments. However, direct measurement of bone strain and joint contact force is challenging and invasive. In the last decade, significant advances in subject-specific musculoskeletal and finite element (FE) models have been made, allowing for accurate prediction of bone strain and joint contact force. My lab developed a human upper extremity loading model to investigate the relationship between bone strain and bone adaptation in healthy adults. We use subject specific FE models to estimate bone strain during a simple task, leaning onto the palm of the hand, which is prescribed as an intervention. Our models were validated with cadaveric strain gauge measurements.

However, more complex functional tasks such as walking and running cannot be easily replicated using cadavers. To move the field forward, our group and others have proposed using a combination of musculoskeletal and finite element models to estimate bone strain during functional activities. For validation, we must rely on experimentally collected joint contact forces and *in vivo* strain gauge measurements. This workshop will highlight experimental and computational methods for estimating *in vivo* joint contact forces and bone strains.

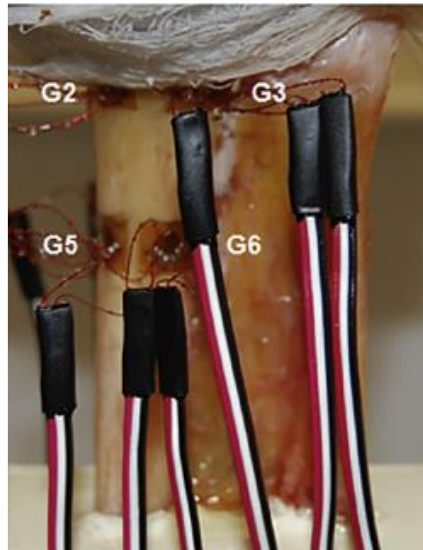


Figure 1 Strain gauges glued to a cadaveric radius for validation of subject-specific FE models.

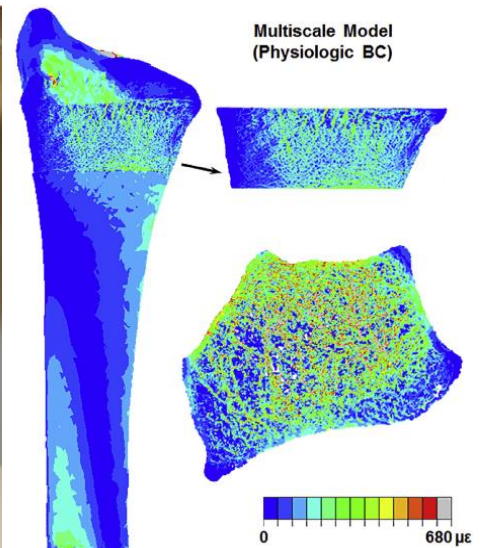


Figure 2 Multi-scale subject-specific FE model showing strain distribution within the trabecular microstructure. Surface strains were validated with strain gauges.



2. In vivo measurement of knee joint contact forces

Darryl D. D'Lima, MD, PhD, Professor & Chair, Orthopaedic Research, Scripps Clinic, CA ddlina@scripps.edu

Instrumenting implants makes it feasible to measure joint contact forces in vivo. We and others have reported on in vivo forces measured in patients with instrumented tibial trays after total knee arthroplasty. Knee forces have been measured under a variety of conditions ranging from activities of daily living, to rehabilitation and exercise, to athletic activities. The significant effects of orthotics, braces, aquatic exercise, and anti-gravity treadmills on knee forces has been reported. Field testing revealed that walking generated significantly different forces depending on the terrain. The data generated has been used as inputs for finite element analysis and for validation of inverse dynamics models. Finally, the datasets generated are made publicly available for unrestricted use by the biomechanical community (<https://simtk.org/projects/kneeloads>, <https://orthoload.com/>)

While the above findings are relevant to total knee arthroplasty, the data generated provide a means for computing underlying bone strains. Directly measuring joint forces or bone

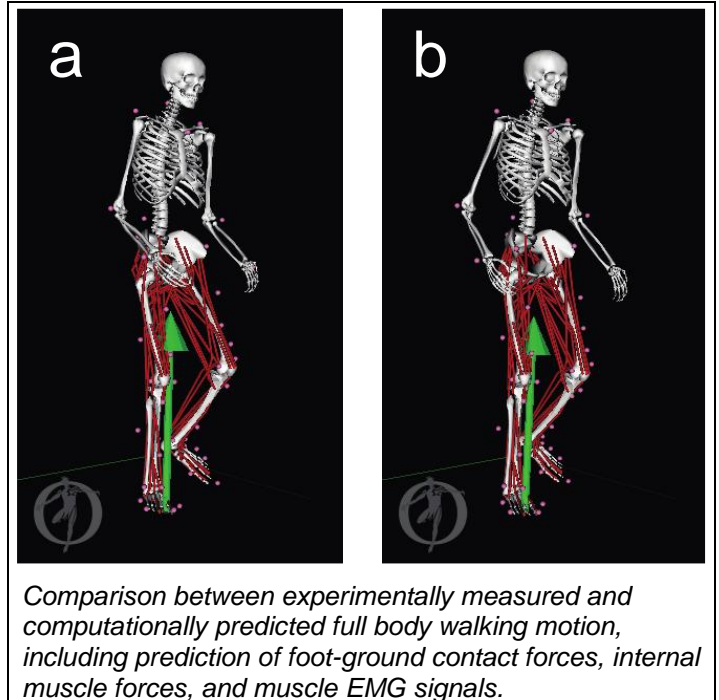
strains *in vivo* is technically challenging and exposes the subjects to some risk. Computational models based on or validated with experimental measurements can be extremely useful to predict outcomes that are currently impossible to measure and to broaden the applications to other musculoskeletal areas.

3. Computational estimation of functional loading in musculoskeletal tissues

B.J. Fregly, Ph.D., Professor and CPRIT Scholar in Cancer Research, Rice University, Houston, TX

Knowledge of the internal forces acting on musculoskeletal tissues (muscles, ligaments, cartilage, bone) during functional activities could facilitate the design of tissue engineered constructs, implantable and external medical devices, orthopedic surgical procedures, and rehabilitation treatments. However, it is not possible to measure internal body forces *in vivo* as part of standard clinical care, leading researchers to develop computational models that can provide estimates. In the internal force estimation process, muscle and joint contact forces play a critical role, since they directly or indirectly affect bone, cartilage, and ligament loads, along with joint motion.

This talk will focus on estimation of *in vivo* muscle and joint contact forces using neuromusculoskeletal computer models. The talk will be divided into two parts. The first part will address current challenges in estimating the *in vivo* functional loads experienced by musculoskeletal tissues. These challenges include muscle redundancy, computational bottlenecks, inverse dynamic errors, calibration of critical model parameters, and validation of estimated internal forces. The second part will address current opportunities for overcoming these challenges. These opportunities include the use of intramuscular pressure measurements to evaluate *in vivo* muscle force estimates, muscle synergy concepts to constrain muscle force estimates, surrogate modeling to speed up deformable joint contact simulations, statistical shape modeling to approximate patient-specific bone geometry, and knee contact force measurements to evaluate *in vivo* knee load estimates. A concluding example will demonstrate how many of these opportunities are currently being combined to develop personalized orthopedic surgical plans and pelvic implants for individuals with pelvic sarcoma.



4. A practical guide for performing human *in vivo* bone strain measurements

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Performing *in vivo* strain gauge measurements is challenging. While digitalization and recording systems have improved since the first human *in vivo* bone strain gauge measurements were reported in the 80's and 90's, the basic problems inherent in performing such measurements remain. This practical guide is presented by someone whose bones have been strain gauged five times and who has performed more than ten such operations on others. For those thinking about performing such experiments, it will help them realize what they are undertaking and how they can lessen potential problems. It is suggested for best utilization of any future study that it be planned as part of developing a finite element model.

1.) IRB approval

- Approval is more likely to be given for subjects who are members of the research team rather than for compensated "volunteers"

2) What study subjects need to know

- >50% chance that incomplete, little or no useful data will result from the experiment.
- Good anesthesia achieved with local Marcaine

- Bonding of surface strain gauges to bone with Histoacryl glue is an off label use and not approved by the FDA.
- Direct surgical incision over bone with poor soft tissue coverage such as the medial tibia border is not a recommended surgical approach.
- The radiation for a tibia CT needed to develop a FEA model is small (0.32 mSv = 3 chest x-rays.)

3) Surface strain gauges

- Advantage- they allow for the possibility of recording compression, tension and shear strains.
- Stacked rosette gauges are too stiff for good mounting to bone so unstacked gauges should be used
- The surgical technique is invasive because a wide area of periosteum must be removed to properly develop and prepare the bone for surface strain gauge application.
- After the periosteum is removed vigorous defatting of the bone by scrubbing with alcohol needs to be done. Some bones are more "greasy" than others and defatting is hard to achieve.
- Surface strain gauges have poor moisture resistance
- Wire breakage is frequent close to the soldering points on the gauge and if it occurs there is no access to them because the surgical wound is closed after gauge application. Strain relief of gauge wires is crucial.
- Bonding a surface strain gauge to bone using PMMA is an alternative and can achieve a stronger bond than Histoacryl. It requires the same defatting and then punching of the bone surface with a fine forked punch to help facilitate PMMA bonding to bone.

4) Instrumented Bone Staples

- Based on a 16 x 15 mm bone staples with a strain gauge mounted to the underside of the bridge
- minimally invasive surgical technique
- Surgical wound is left open for the duration of the experiment
- Good for uniaxial measurement, best used for intra subject comparison trials
- Excellent correlation with surface strain gauge but the coefficient factor varies between anatomical sites and the staple used.
- Rosettes formed by a cluster of instrumented bone strains do not correlate with rosette surface strain gauges.

5) General rules

- Check and evaluate the strain gauge output frequently during the experiment to verify the system is working correctly.
- Mount a back-up gauge when using surface strain gauges
- Give prophylactic IV antibiotics to the subject before strain gauge application and at time of removal to help prevent wound infection.

5. Relevant resources and references

- OpenSim software: <https://simtk.org/projects/opensim>
- Grand Challenge Competition to predict in vivo knee loads: <https://simtk.org/projects/kneeloads>
- Data from other instrumented prostheses: <https://orthoload.com/>
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