Project 1

Biomechanical Evaluation of Knee Savers for Reducing Joint Load during Squatting

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Background

- Osteoarthritis (OA) is a chronic disease that affects 32.5 million people (10% men and 13% women) in the U.S. (Zhang 2010; CDC 2020)
- Overloading the knee joint causes degenerative development of the articular cartilage, leading to knee OA (Osborne 2019)
- Prevalence of knee OA among workers are associated with their occupational activities: occupations involving high knee-flexion tasks resulted in increases in knee OA occurrence from 122% (Felson 1991) to 240% (Cooper 1994), compared to normal population
- In 2019-2020, there were 3.1 million frontline wholesale retail workers, 217k roofers, 699k carpenters, and 901k electricians in U.S. (BLS 2020) – they all may need to perform high knee-flexion tasks in their jobs
- OA is an age-related joint disorder – old workers are more likely to develop OA compared to average workers and knee OA for older people may be a consequence from prior work-related knee injuries (Anderson 2010; Dulay 2015)
- The average age of construction workers increased from 40.5 to 42.5 years in the last seven years (BLS 2020) and later-career workers (55-75 y) accounted ~22% entire wholesale retail workforces (Loprest 2019)
- Average lifetime medical costs for a person diagnosed with knee OA were over $140,300 (Losina 2015)

Background

- **Knee savers are devices that are attached to the users' legs to make it more comfortable during high knee-flexion tasks; knee savers are used in sports and by some construction workers**
- **Knee-saver devices have been developed traditionally via a *fit and try* method**
- **Knee-saver devices' effects in reducing knee joint loading have not been analyzed biomechanically**

Knee support devices

A: Knee braces; B: Knee savers (foam); C: Knee aid (spring)

Knee-saver devices

Hypotheses

- **Use of knee-saver devices reduces the joint contact forces, making users feel more comfortable when performing high knee-flexion tasks**
- **Use of knee-saver devices changes squatting postures, thereby affecting loading in the spinal muscles**
- **Existing knee-saver devices are not optimized for all users and for different tasks to reduce the musculoskeletal loading in the knee joint**

Research Design – Aim 1

Development of 3D biomechanical models

An existing whole-body human model with detailed anatomical components of the knee will be adopted and modified for the analysis

- The proposed biomechanical model contains:
  - Tibiofemoral (TF) and Patellofemoral (PF) joints
  - Detailed lower extremity with 159 muscles
- The effects of the mass and inertia properties of the upper extremity, trunk, neck, and head will be considered in the modeling
- **Model inputs**: (1) kinematics of the human body, (2) contact forces on the legs and thighs
- **Model outputs**: (1) muscle forces, (2) the joint contact forces in TF and PF, and (3) ground reaction forces (GRFs)

3D biomechanical models

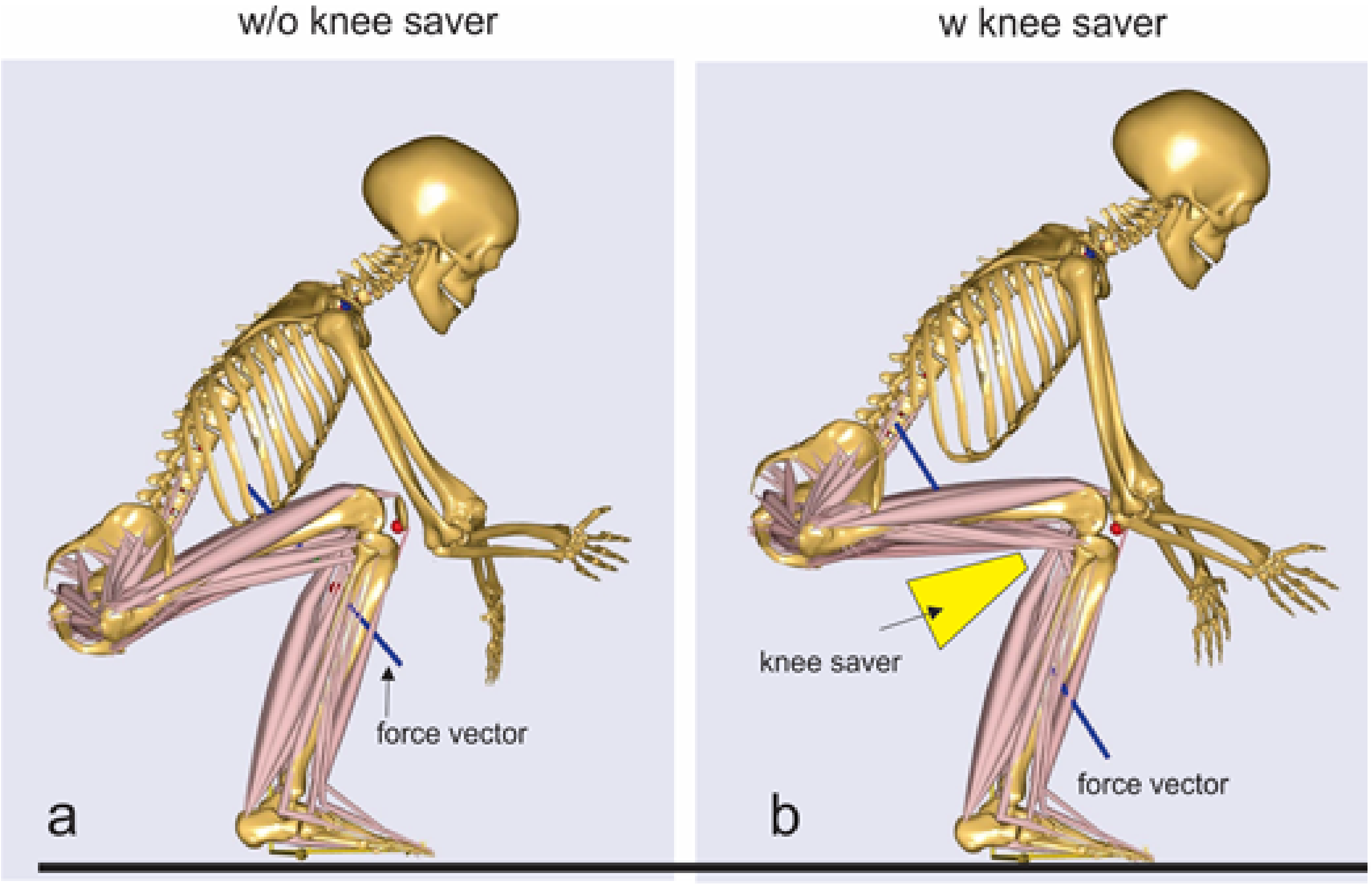
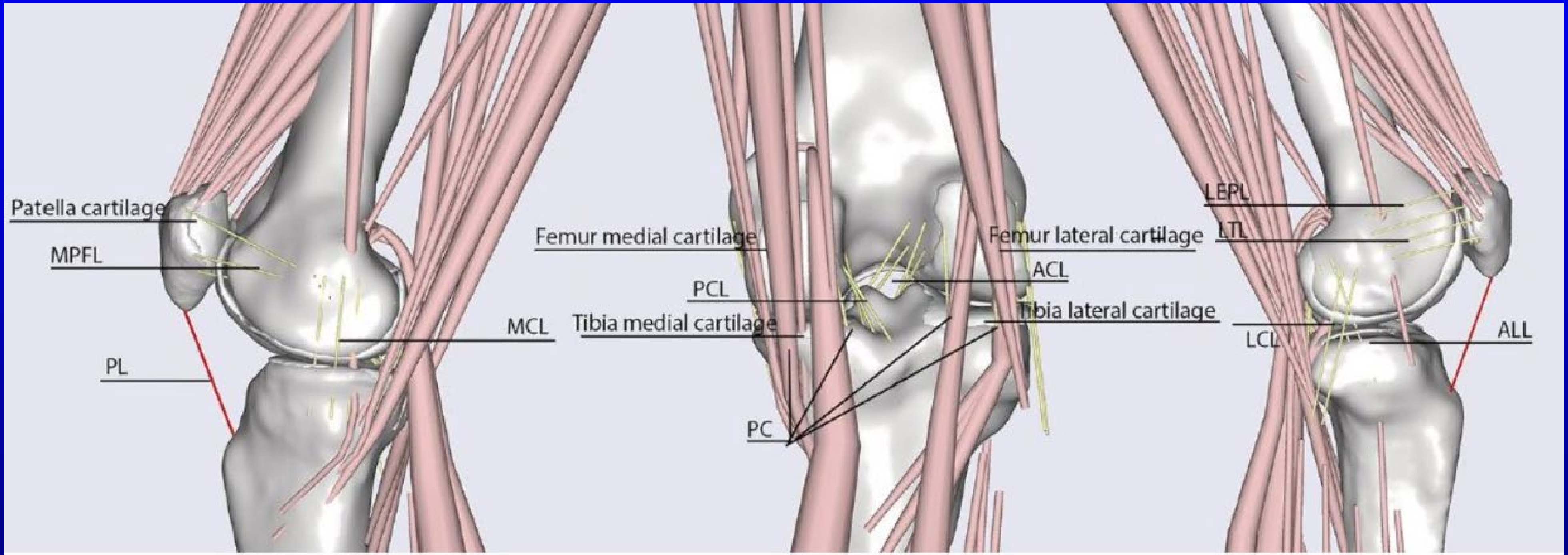


Figure 1: Biomechanical model of deep squatting without wearing knee saver (a) and wearing knee savers (b).

3D biomechanical models



Medial view Posterior view Lateral view

3D biomechanical models

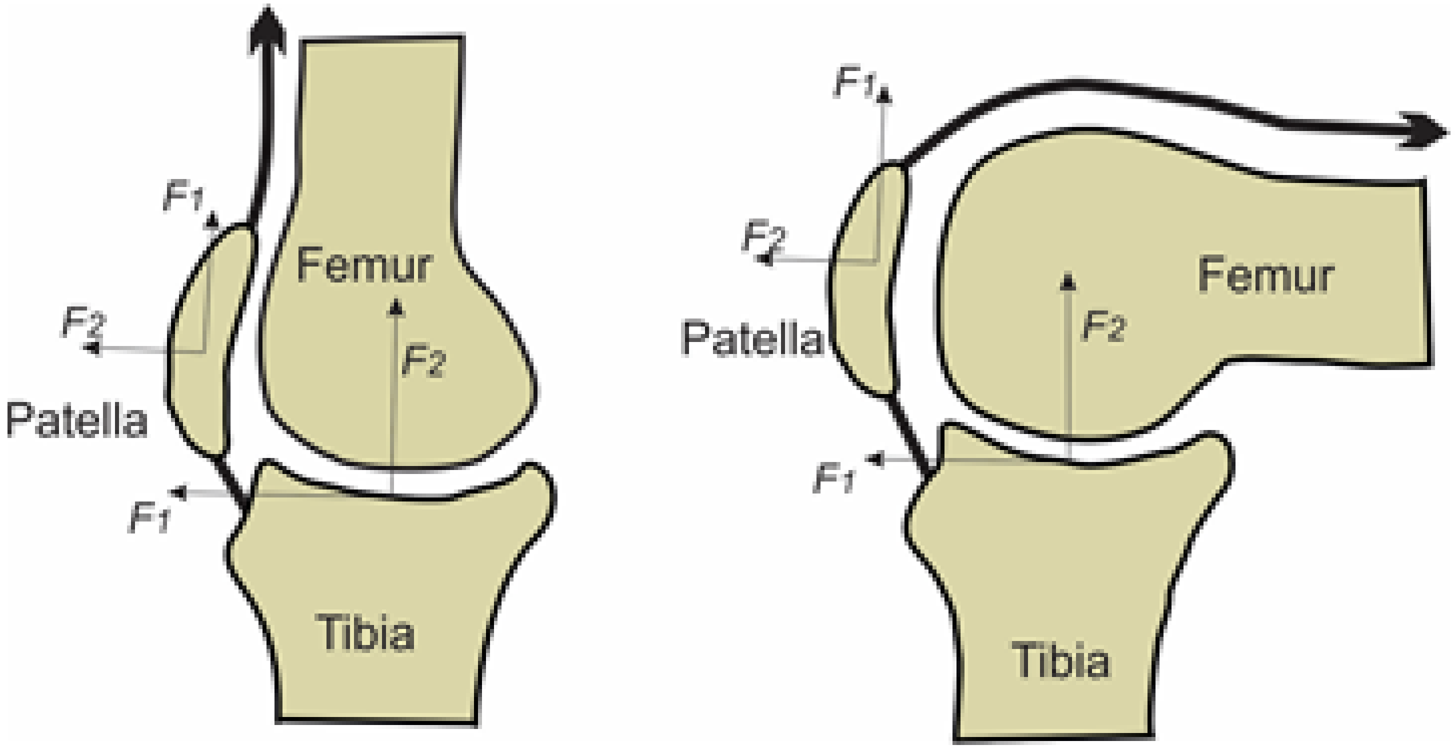


Figure 2: Knee model contains tibiofemoral (TF) and patellofemoral (PF) joints

Research Design – Aim 2

Human subject tests

Healthy subjects (male and female) who have no previous knee OA and can perform deep squatting tasks

- **Two rounds of slow deep squats – without and with knee-saver devices**
- **Two deep squatting postures: heel-down and heel-up squatting**
- **Representative commercial knee savers and customized knee savers will be used**

Measurements:

1. **Subjects' body sizes and the ROMs of the lower extremity**
2. **Kinematics for the human body during the squatting**
3. **Ground reaction forces**
4. **Thigh/leg interface contact pressure/forces**
5. **EMG: muscular activities of the quadriceps and hamstrings muscles and selected spinal muscles**

Human subject tests

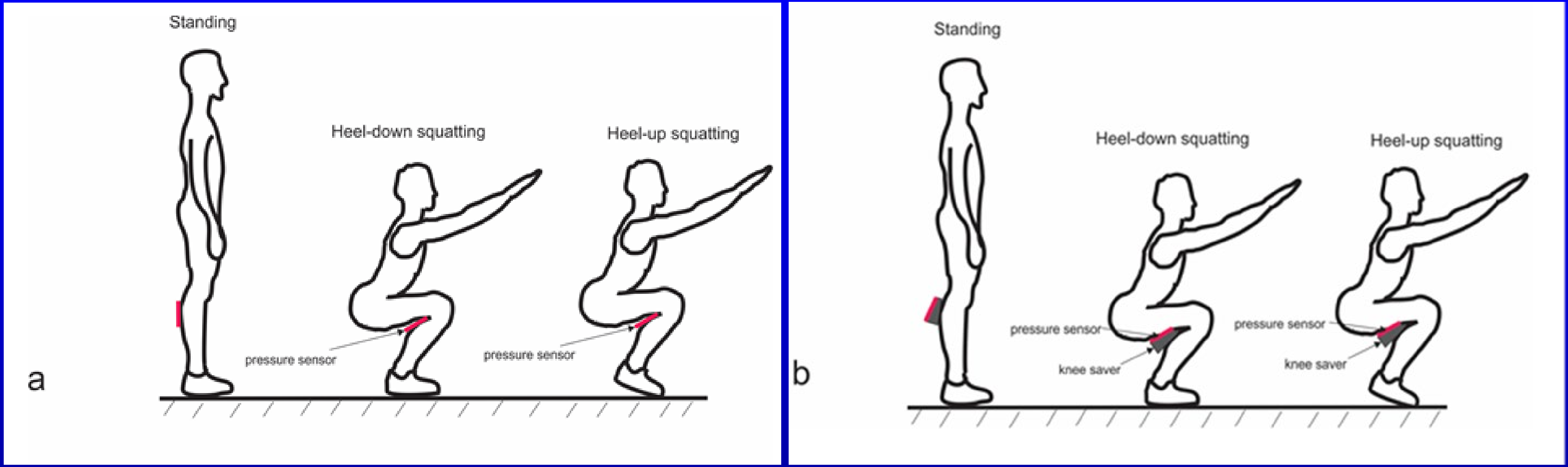


Figure 3: Test procedure. Subjects will perform heel-down and heel-up squatting with (b) and without wearing knee savers (a).

Research Design – Aim 3

Improving the design of knee-saver devices

- 3D prototypes of the knee savers will be digitally built using SOLIDWORKS software
- 3-4 variations for the knee saver design: varying the wedge angle by +/- 5-10 degrees
- Physical knee savers will be made using *rubber-like thermoplastic* materials via a 3D printer; the instrumented knee savers will have sensors to measured contact forces
- The test and evaluation procedures for the customized knee savers:
  - ➢ Human subjects: slow deep squats without knee savers and with knee savers of different designs
  - ➢ Kinematic and kinetic data, the contact pressure in the thigh/leg, GRFs, EMG will be collected
  - ➢ Biomechanical analyses

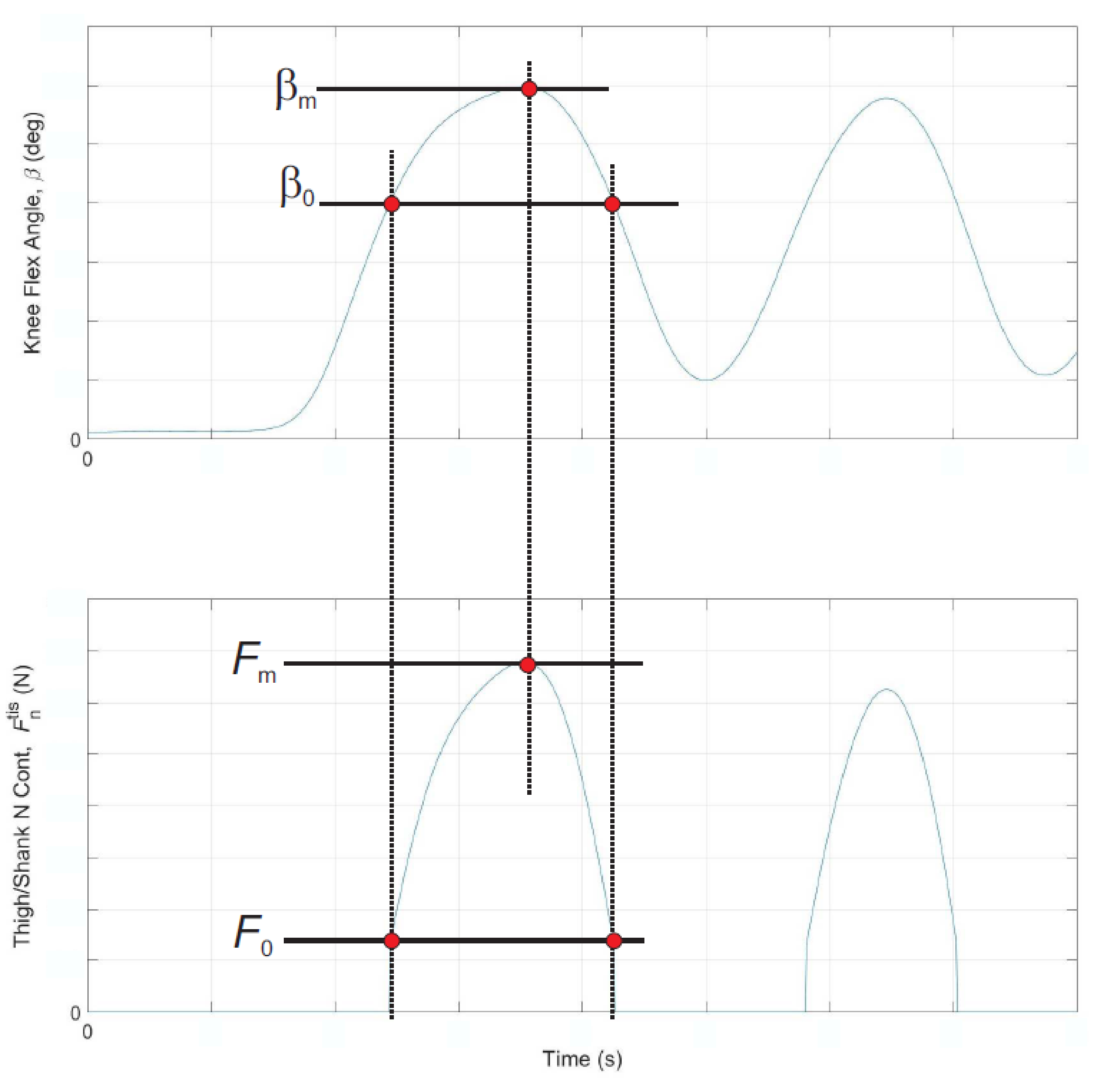
➢ Performance of different knee saver designs will be objectively evaluated by *joint contact forces* and muscle activities measured via *EMGs*

Project progress: human subject test

- A service contract with NIU (Northern Illinois University) to perform pilot human subject tests (1-2 subjects) has been awarded
- Human subject testing protocol has been approved by IRB of NIU
- Testing setup has been developed
- Pilot human subject testing is in progress
- A human subject test protocol has also been prepared and submitted to NIOSH IRB

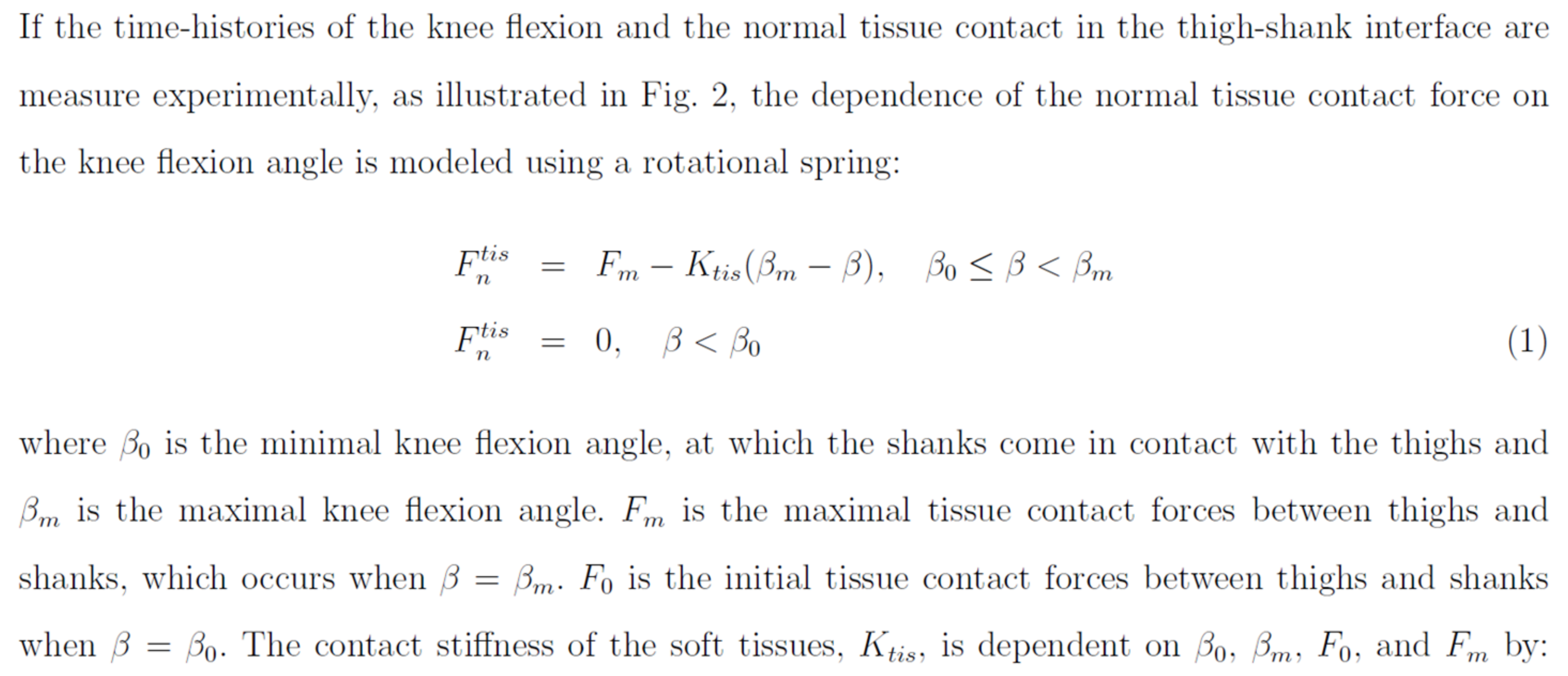
Measurement of soft tissue contact pressure

Determination of parameters for the internal soft tissue contact



Project progress: biomechanical modeling

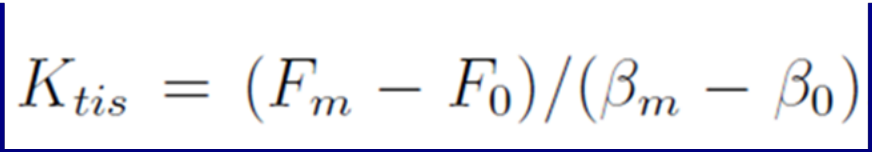
-- Modeling of the internal contact of deep squatting tasks --



If the time-histories of the knee flexion and the normal tissue contact in the thigh-shank interface are measure experimentally, as illustrated in Fig. 2, the dependence of the normal tissue contact force on the knee flexion angle is modeled using a rotational spring:

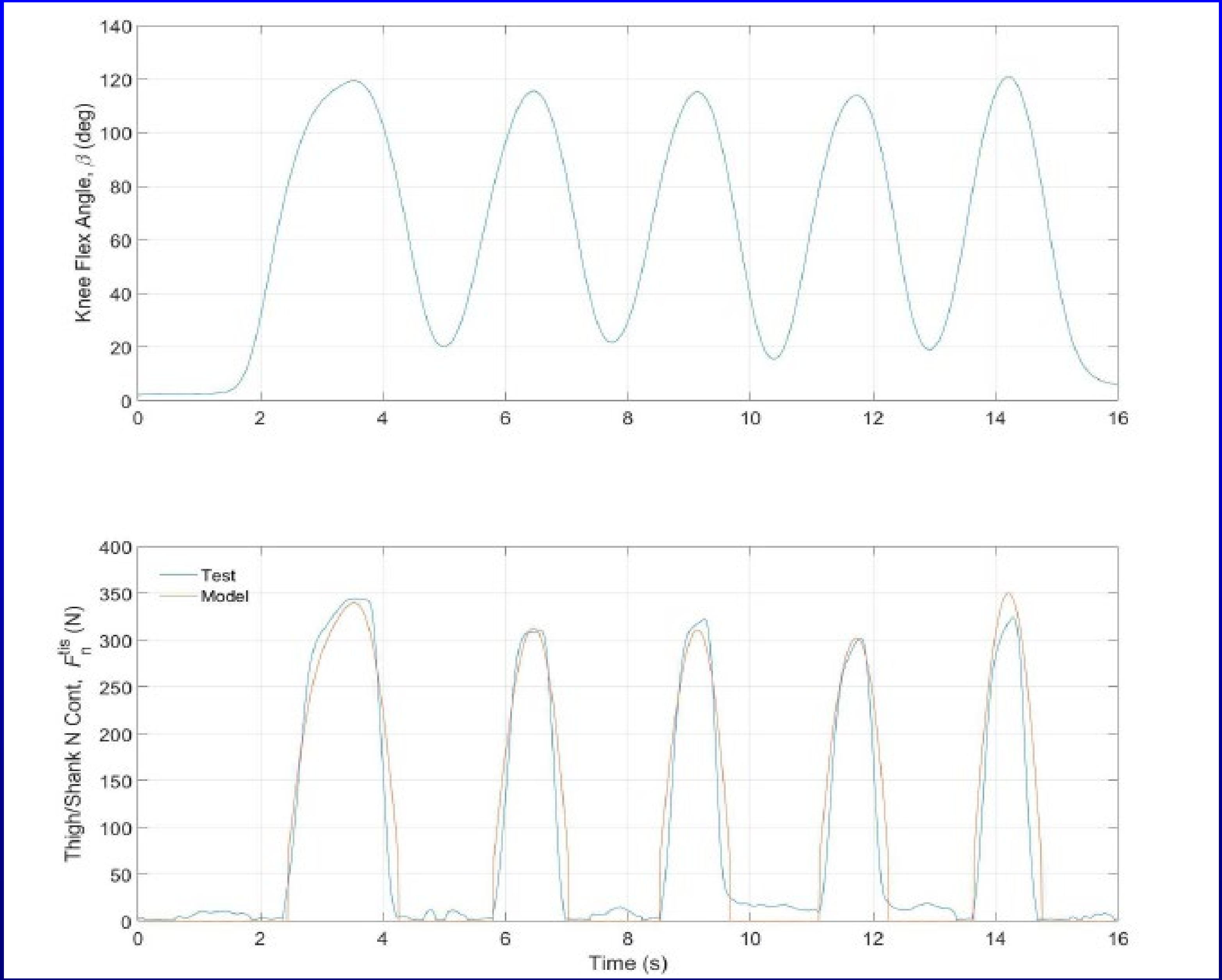
$$
\begin{aligned}
F_n^{tis} &= F_m - K_{tis}(\beta_m - \beta), \quad \beta_0 \leq \beta < \beta_m \\
F_n^{tis} &= 0, \quad \beta < \beta_0
\end{aligned}
\tag{1}
$$

where β_0 is the minimal knee flexion angle, at which the shanks come in contact with the thighs and β_m is the maximal knee flexion angle. F_m is the maximal tissue contact forces between thighs and shanks, which occurs when $\beta = \beta_m$. F_0 is the initial tissue contact forces between thighs and shanks when $\beta = \beta_0$. The contact stiffness of the soft tissues, K_{tis}, is dependent on β_0, β_m, F_0, and F_m by:

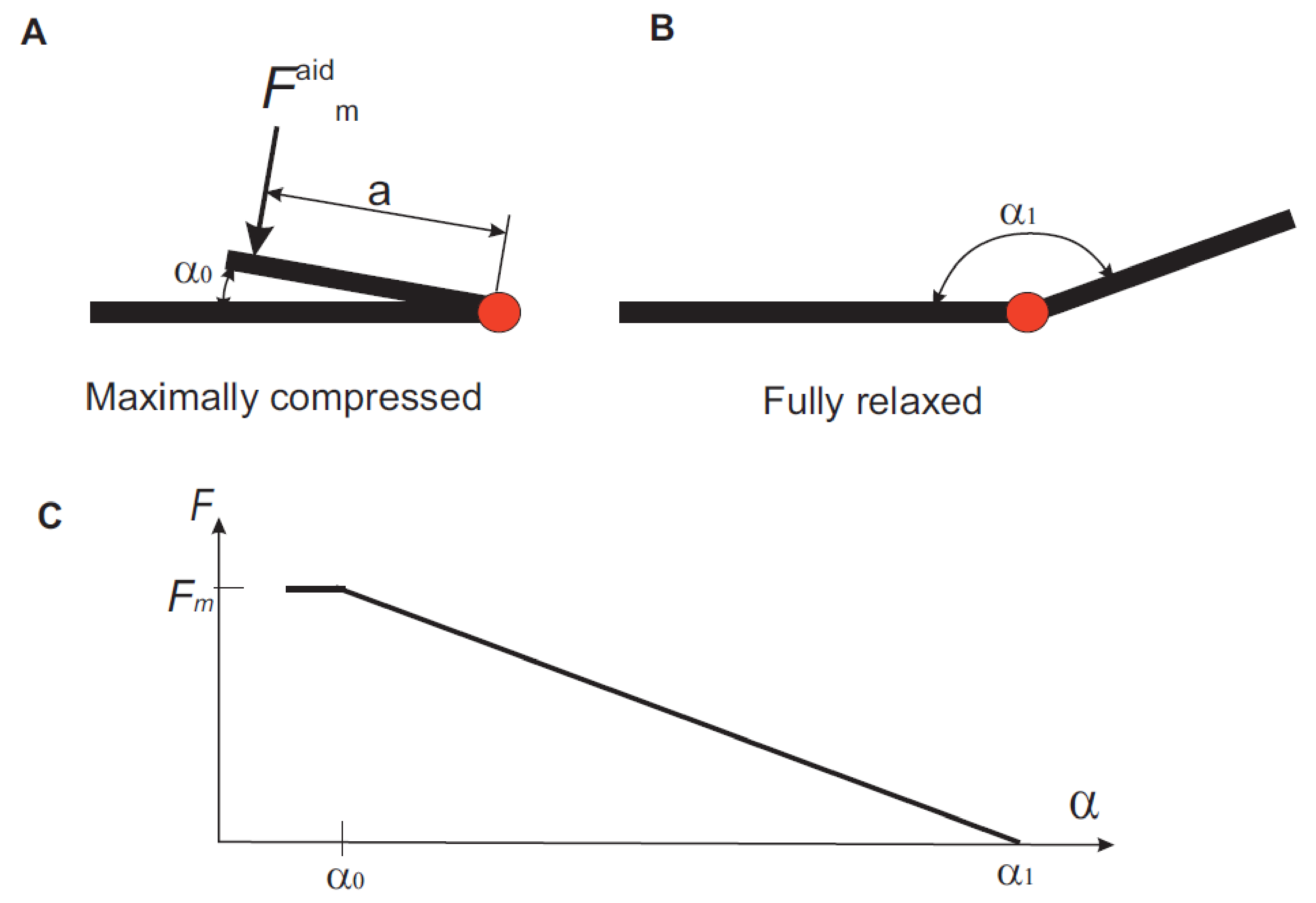


$$K_{tis} = (F_m - F_0)/(\beta_m - \beta_0)$$

Knee flexion angle and soft tissue contact force as a function of time



Analysis of spring knee aid on the musculoskeletal loading at the knees during high knee-flexion tasks



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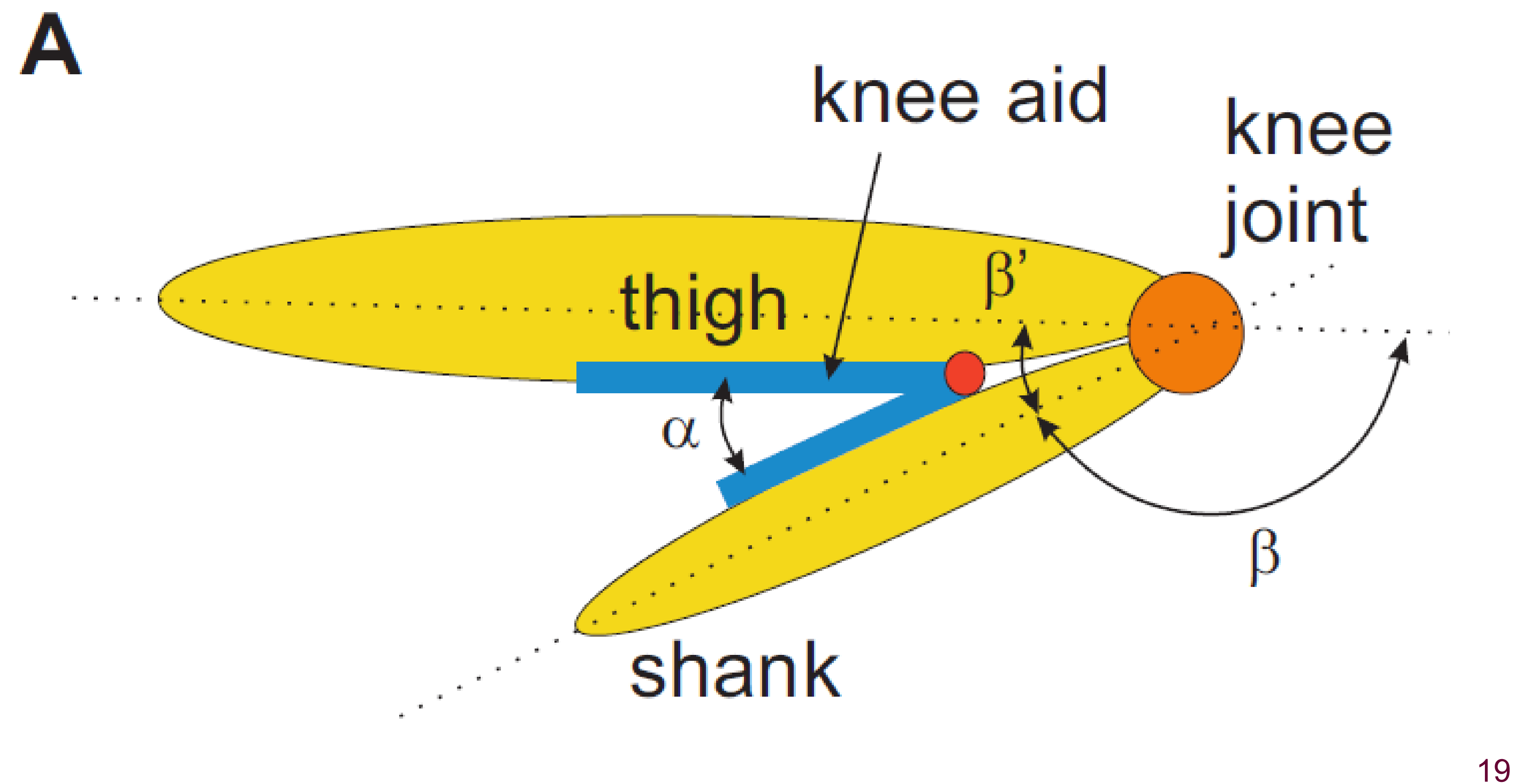
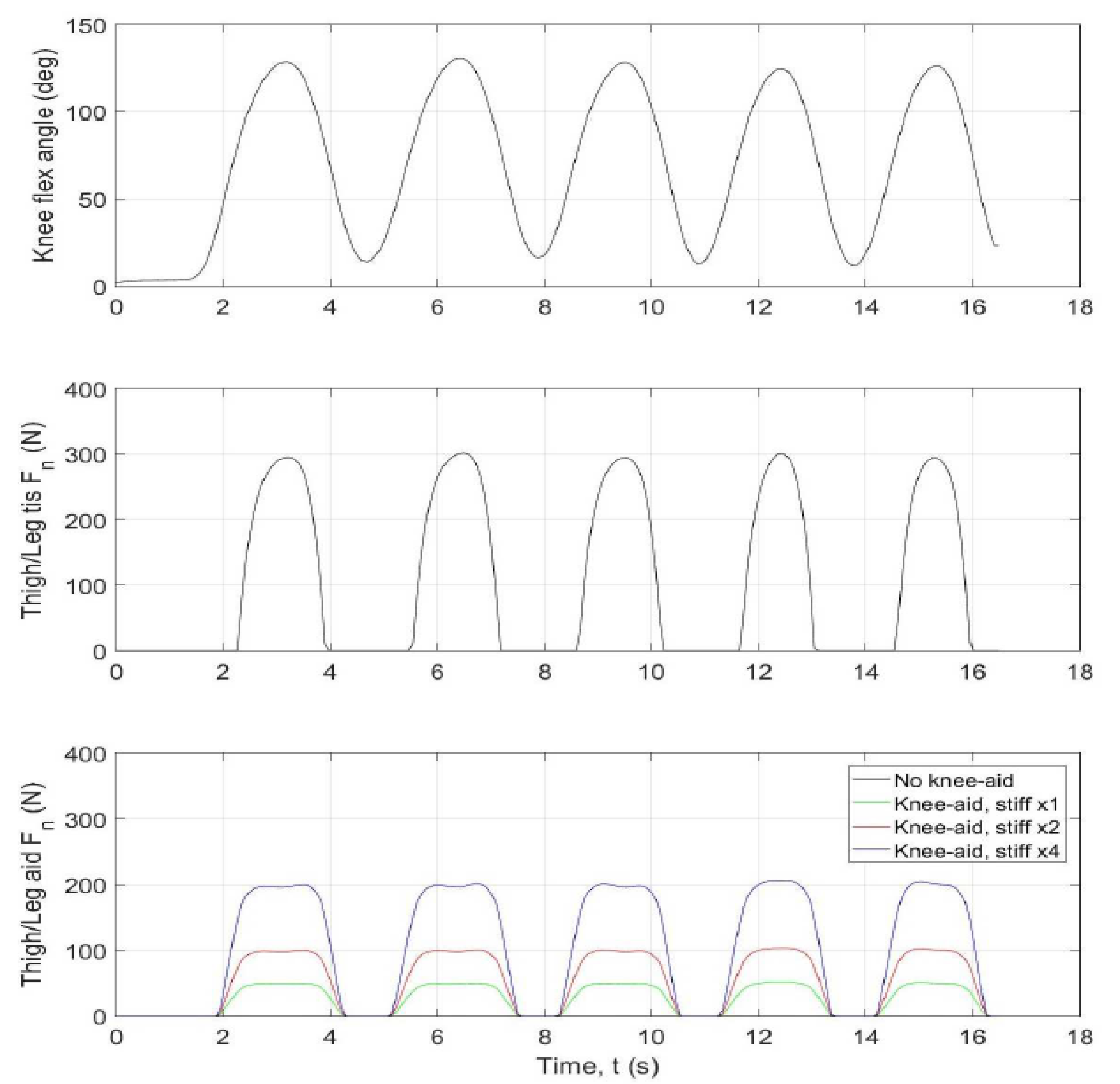
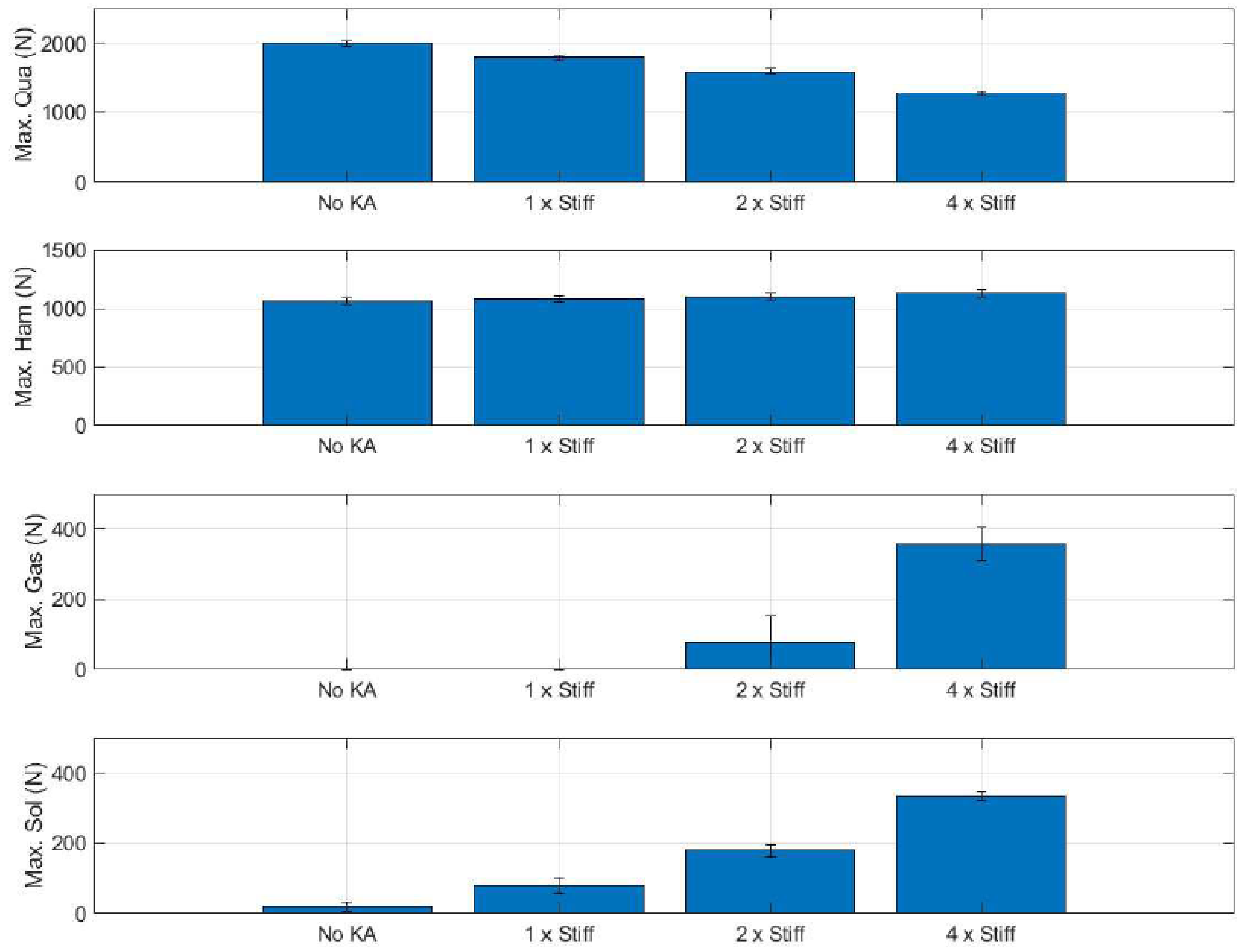


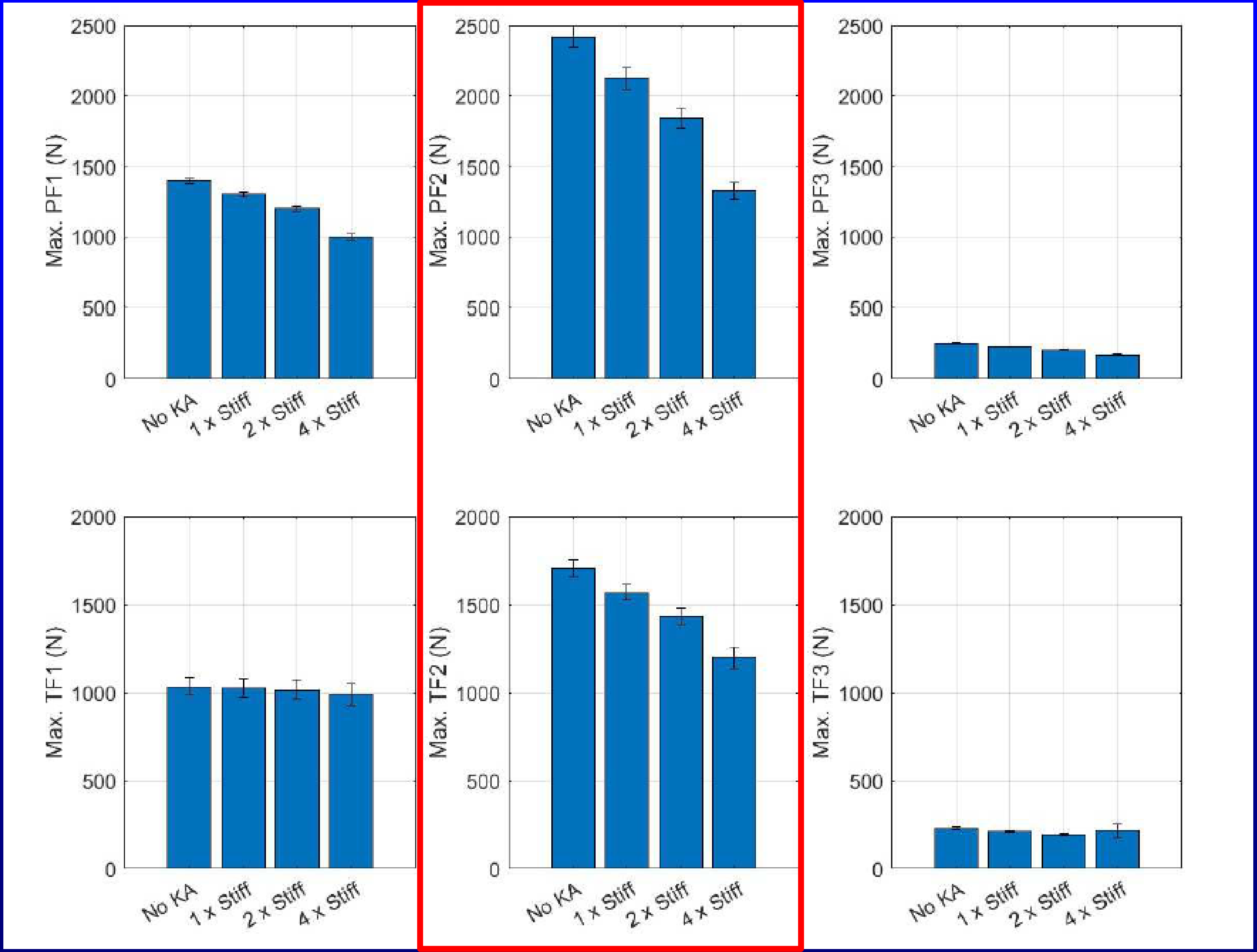
Knee flexion angle, soft tissue and knee aid contact forces as a function of time



Calculated peak muscle forces



Calculated peak joint forces



Manuscripts in preparation:

(1) JZ Wu, KD Moore, L Zheng, T Xia. An approach to determine the contact forces between the posterior thigh and shank during high knee-flexion tasks. To be submitted to: *Journal of Biomechanics*.

(2) JZ Wu, KD Moore, L Zheng, T Xia. Biomechanical evaluation of spring knee aid on the musculoskeletal loading at the knees during high knee-flexion tasks. To be submitted to: *Annals of Biomedical Engineering*.

Project 2

Evaluation of stability, slipping, & intervention methods for roofing workers

Key investigators:

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Background

- There were approximately 153,700 roofers in 2020 and that number is forecasted to progressively increase in the next 10 years. (BOL Statistics 2021)
- Residential roofing workers face both musculoskeletal disorders and traumatic injury risks in their jobs. (BOL Statistics 2021)
- Falls from roofs have been an issue for some time and were the principal source of fatal injuries in 2019, resulting in 146 deaths – a 28% increase from 114 deaths in 2018. (BOL Statistics 2020)
- Construction workers are less likely to return to work after an MSD injury compared with workers in other sectors and roofing workers on average experience 39.2 days away from work per 10,000 FTE. (Shishlov 2011)
- Even if a fall does not lead to a fatality, workers may face many other serious issues, such as traumatic brain injuries, and may require lengthy rehabilitation and recovery, especially for older workers (>50 years). (Leigh 2004)
- The cost of roofing work-related injuries is extremely high: falls to a lower level ($3.56 Billion in healthcare-related costs, which is 33.8% of all construction injuries), handling heavy objects like shingles ($2.21B, 21.0%), falls to the same level ($0.99B, 9.4%), and awkward postures and repetitive motions ($0.67B, 6.4%). (Welch 2010)
- Insurance rates for roofing workers can be nearly three times as high as the average rate of all construction trades. (Ohio_BWC 2015)

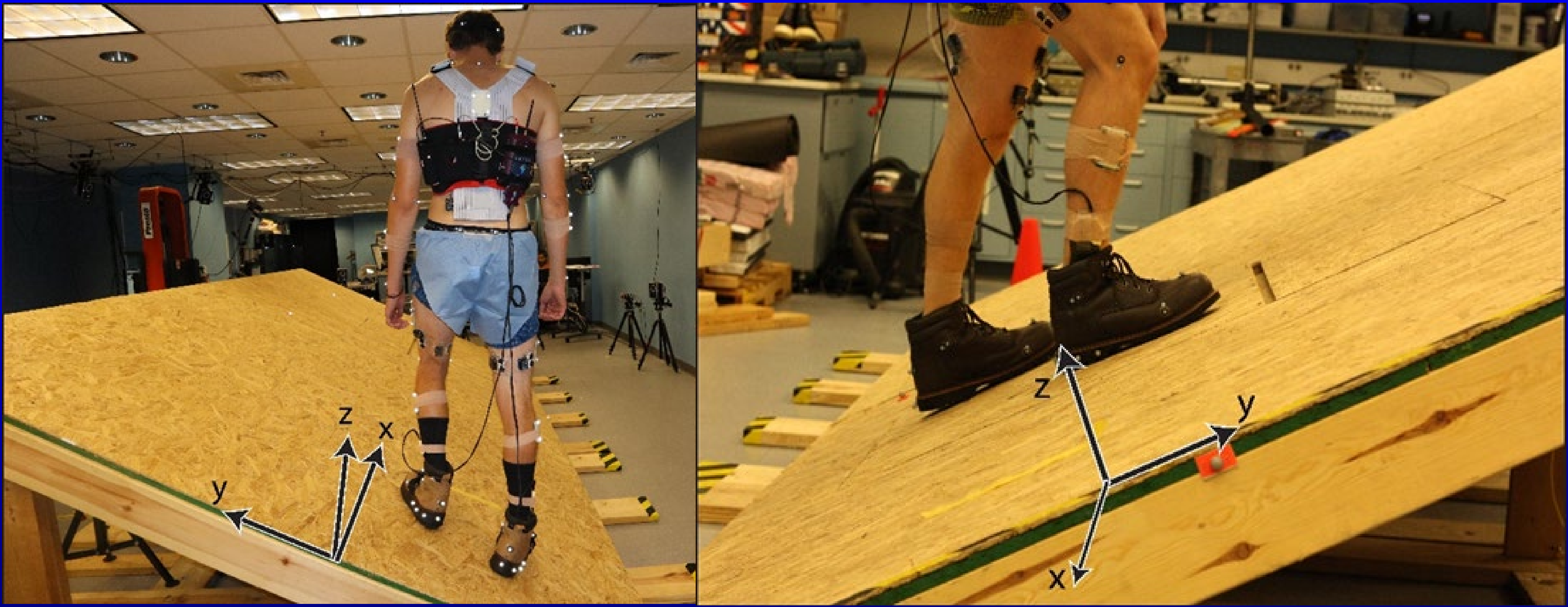
Specific Aims

- **Aim 1** will develop and apply a method for measuring the standing and dynamic stability on a simulated sloped residential roof surface.
- **Aim 2** will develop a biofidelic friction testing method to characterize slip risk associated with residential roof materials.
- **Aim 3** will evaluate two specific residential roofing technologies (Pitch Hopper and RoofSmartPad) to determine if their deployment will alter residential roofing worker postures enough to either improve or reduce stability.

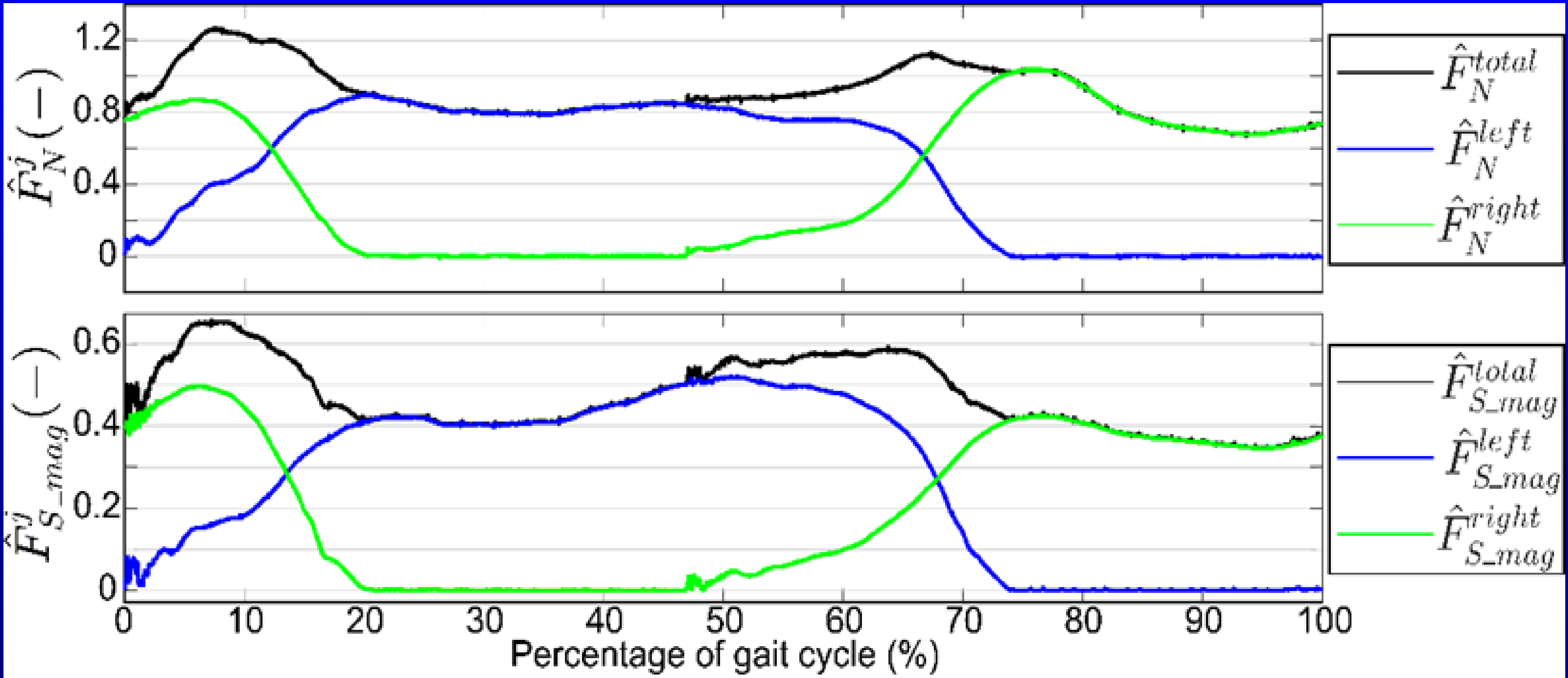
Project progress

- A service contract with PITT (University of Pittsburgh) “Evaluation of stability, slipping, & intervention methods for roofing workers” has been awarded
- IRB Human subject test protocol has been submitted and is in revision
- A test set up to evaluate the slip friction between boots and roofing surface has been developed and in the calibration process
- Analysis of slip/fall potential based on our previously collected data

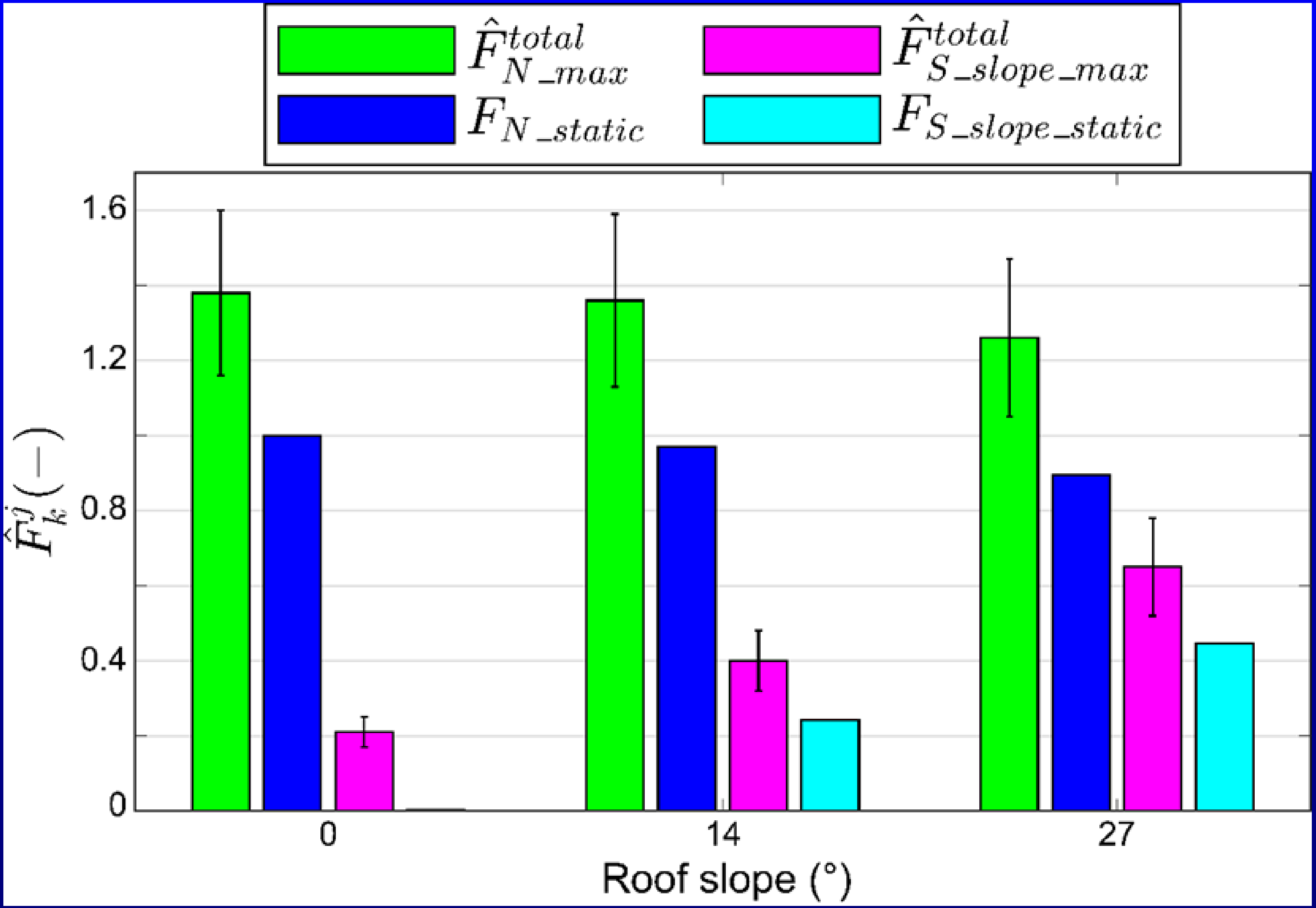
A subject walks on the roof simulator



Sample data of normalized normal force ($\hat{F}_N^j$) and shear force magnitude ($\hat{F}_{S\_mag}^j$) (j=left, right, or total-combination of left and right feet)



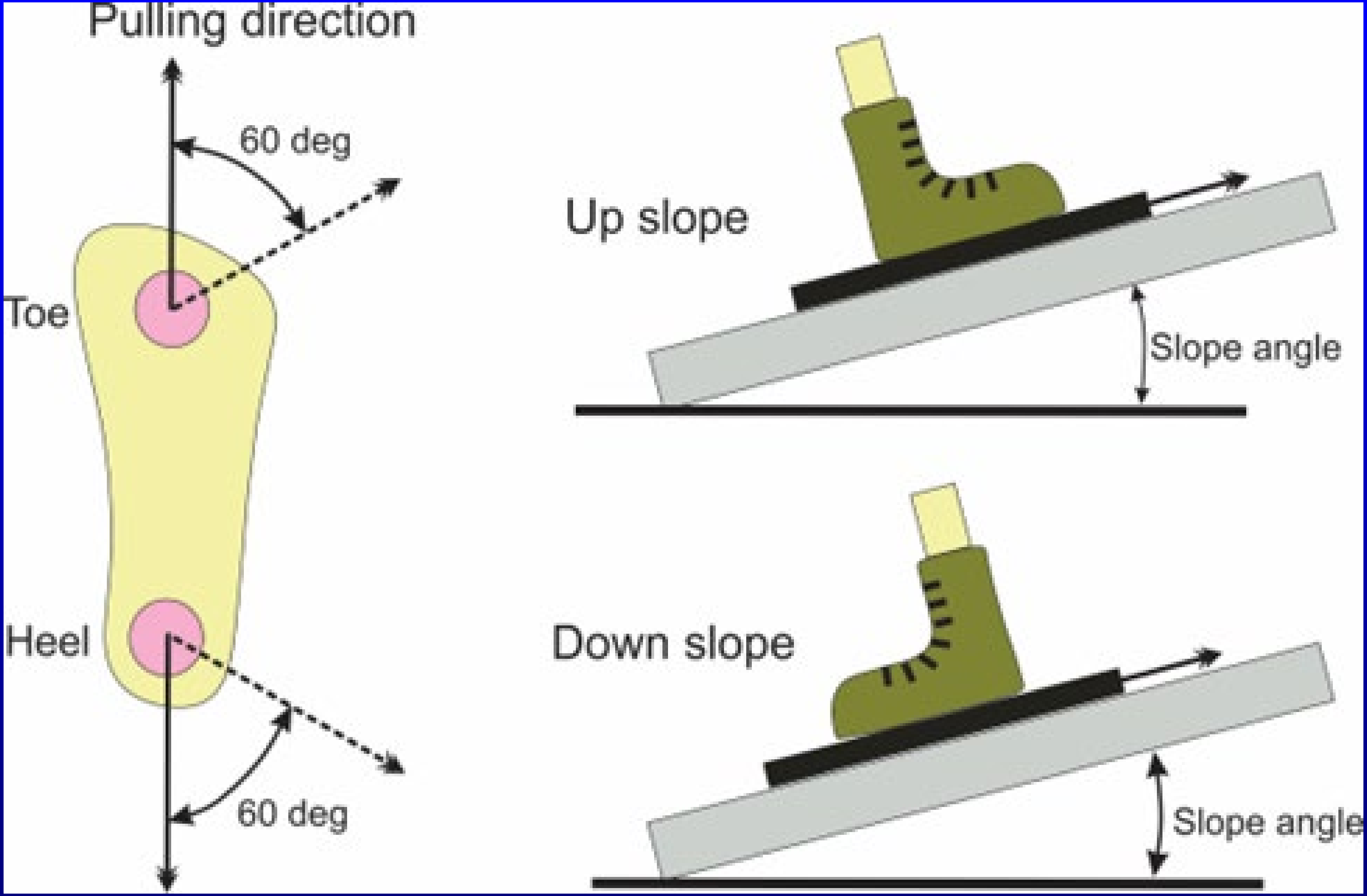
Peak normalized forces as a function of each walking direction



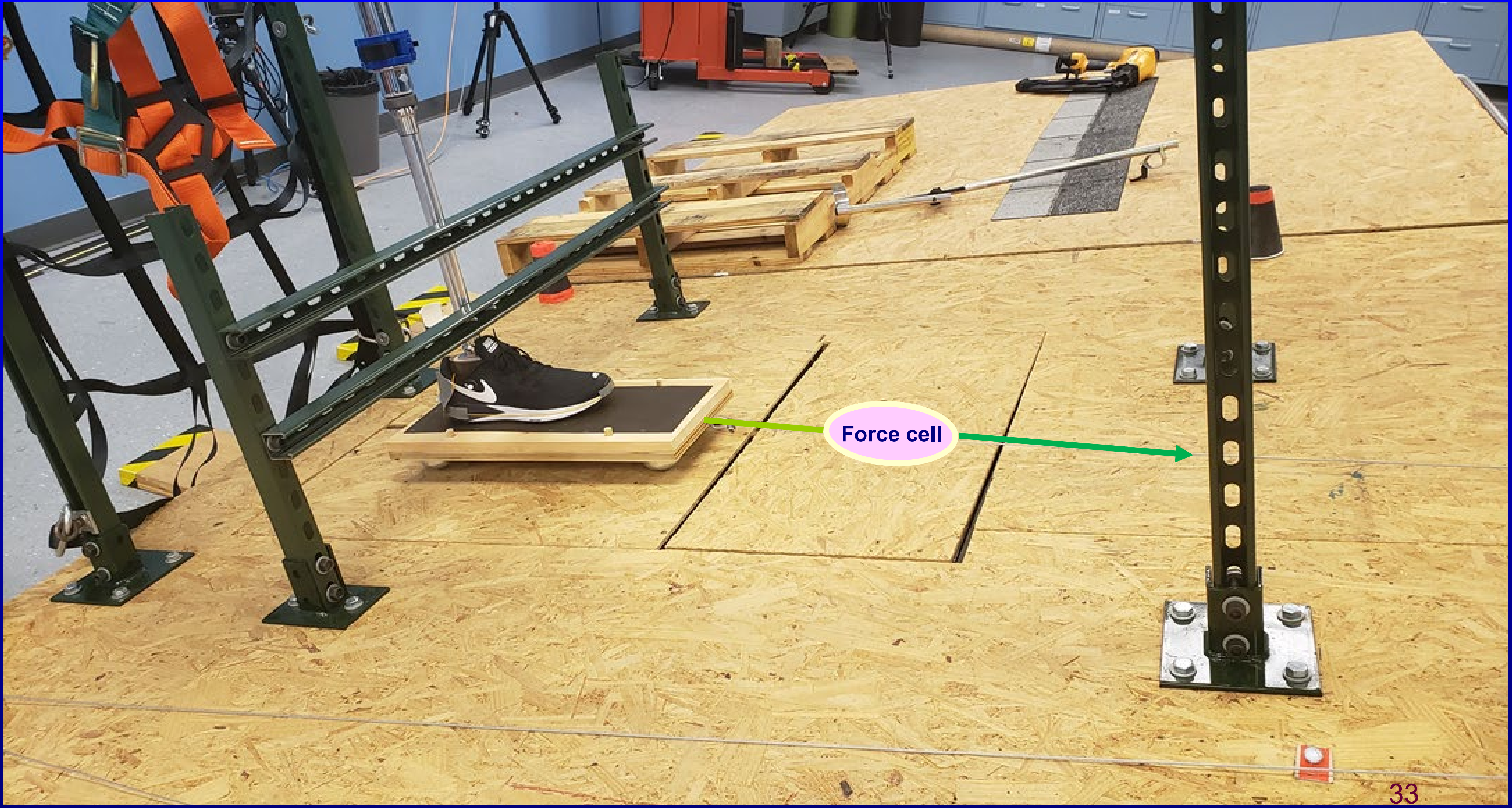
Manuscript in preparation:

(1) RE Carey, JZ Wu, SP Breloff, CM Warren, EW Sinsel, RG Dong. Evaluation of slip potential when walking on a sloped residential roofing surface. To be submitted to: International *Journal of Occupational Safety and Ergonomics*. In NIOSH clerance review.

Proposed measurements of toe- and heel-sliding



Sliding plate system in calibration



Thanks