Novel Distraction-Unloader Knee Braces for Medial Compartment Knee Osteoarthritis

FINAL CAPSTONE PAPER

Spring 2025

Team Members
Mira Zineddin, Anna Dugan

Advisors
Dave Johnson, Cole Yantiss
In Affiliation with Icarus Medical LLC

Max Ronkos
In Affiliation with UVA Health Prosthetics and Orthotics

Word Count: 5,287
Number of figures and tables: 8
Number of equations: 0
Number of supplements: 7
Number of references: 43

Signature:  **Date:** May 3, 2025
Anna Dugan, Department of Biomedical Engineering

Signature:  **Date:** May 3, 2025
Mira Zineddin, Department of Biomedical Engineering

Approved:  **Date:** May 5, 2025
Dave Johnson, Icarus Medical

Approved:  **Date:** May 5, 2025
Max Ronkos, UVA Health Prosthetics and Orthotics

Novel Distraction-Unloader Knee Braces for Medial Compartment Knee Osteoarthritis

Mira Zineddin[a], Anna Dugan[b], Max Ronkos[c], Cole Yantiss[d], Dave Johnson[e,1]

[a,b] University of Virginia Biomedical Engineering Department, Charlottesville, VA
[c] UVA Health Prosthetics and Orthotics, Charlottesville, VA
[d,e] Icarus Medical, Charlottesville, VA
[1] Correspondence: dave@icarusmedical.com, 609 E Market St #114 Charlottesville VA 22902, 434-242-0258

Abstract

There is a growing demand for non-surgical medial compartment knee osteoarthritis (OA) treatments. Current options, such as intra-articular injections, are mainly palliative—offering symptomatic relief without addressing the root causes of pain.[1] Knee braces are a promising treatment given their low-risk and customizable designs, with trials already indicating significant cost-effectiveness and possible postponement of OA progression.[2] However, key challenges remain with traditional unloading braces, and advancements are needed to improve brace usability to support long-term patient compliance and establish robust clinical and biomechanical evidence of their effectiveness. Focusing on the novel Adonis® distraction-unloader knee brace from Icarus Medical, we laid the groundwork for a three-pronged approach aimed at improving brace development: (1) optimizing ease of use by simplifying the brace's clip-strap system, (2) prototyping a biomechanical knee model to measure changes in vertical knee compartment loading, and (3) initiating a single-arm prospective clinical trial that incorporates patient-reported outcomes for monitoring quality of life, ultrasound imaging to measure joint-space width, and gait analysis to observe leg functionality. The ease of use of the brace was successfully improved by generating a merged clip system; however, this slightly limited the independent flexibility of the straps. A knee model capable of sensing force changes in the medial and lateral compartments showed strong proof of concept for assessing the effect of brace wear on intra-compartmental knee loading. The clinical trial protocol was drafted and submitted for approval following literature review.

Keywords: Knee orthotic, distraction-unloader knee brace, distraction biomechanics, osteoarthritis

---

Introduction

Knee Osteoarthritis Pathophysiology

Knee OA is the most common orthopedic disorder in the U.S., affecting around 1 in 3 people within their lifetime.[3] Globally, knee OA accounts for roughly 60% of all OA cases and affects over 365 million people.[4] Knee OA is a degenerative condition that impacts all parts of the joint, leading to the loss of cartilage, subchondral bone attrition, neuromuscular impairments, ligament laxity, fat pad impingement, meniscal degradation, and lower-limb malalignments.[5]

From a biomechanical perspective, these OA-induced structural changes create abnormal loading on the knee, further accelerating OA progression. OA development thus follows a cyclical pattern, where abnormal loading on healthy tissue and normal loading on damaged tissue both contribute to OA worsening. The inner part of the knee—known as the medial compartment—bears the greatest load, so it is most commonly impacted by knee OA. For example, the medial compartment bears up to 80% of loading during the mid-stance phase of gait.[5] As such, the medial compartment is afflicted in 72% of knee OA cases.[6] OA-induced erosion of the medial compartment commonly leads to varus knee,[7] a lower-limb malalignment also known as bowleggedness, which further exacerbates abnormal loading on the knee joint.

Significance of Non-Surgical Osteoarthritis Options

The exact causes of OA are unknown, and there is no cure. Once end-stage OA is reached, surgery is currently the only reliable option. The gold-standard

treatment is total knee replacement (TKR), where an artificial implant substitutes the entire knee (Fig. 1A). Other surgical options include unicompartmental knee replacement (UKR) (Fig. 1B), where only half of the knee is replaced;[8] high tibial osteotomy (HTO), which involves cutting the tibia to relieve loading on the medial compartment and correct the knee alignment (Fig. 1C); and external distraction fixators, which aim to relieve loading on the medial compartment by increasing joint-space width (Fig. 1D).[9]

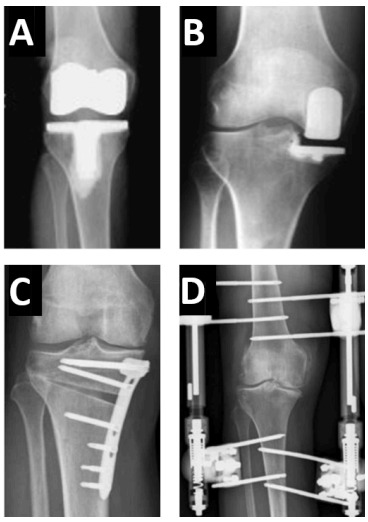

Fig. 1. Medial compartment OA surgical options. (A) Total knee replacement; (B) Unicompartmental knee replacement;[8] (C) High tibial osteotomy; (D) External distraction fixators[9]

Though the specific contraindications vary by procedure, all surgical options for knee OA have similar disadvantages, including high costs and the potential need for revision surgery.[10] Surgery also has inherent access barriers and risks, such as the need for operating rooms and specialized medical teams, comorbidities that conflict with surgery or anesthesia, the risk of scarring or operative complications, lengthy recovery times, and extensive follow-up care and rehabilitation. These surgical access barriers have contributed to OA outcome disparities that disproportionately affect women,[11] racial minorities, low-income individuals, underserved areas,[12] and those with multimorbidity.[13] As a result, many patients endure years of disabling knee OA before undergoing TKR, with 83% of patients waiting longer than 2 years even when TKR becomes appropriate.[14]

Moreover, many knee OA patients are suboptimal surgery candidates due to factors like age, comorbidities, and limited activity levels or social support. Although TKR is ideally delayed until the age of 70 due to the implant's approximate 20-year lifespan, nearly half of TKRs are performed on patients under 65.[15] Successful recovery from major knee surgeries like TKR also heavily depends on consistent exercise, physical therapy, and family support, which are not feasible for every patient.[16] All of these factors highlight the need for earlier, non-surgical interventions and more accessible options for knee OA.

As such, it would be ideal to develop more effective non-surgical OA treatments that could serve as both early and late interventions that delay or eliminate the need for surgery. Current options include intra-articular injections, weight loss, dietary changes, analgesics, physical therapy, and standard-of-care bracing. However, these options often only provide symptomatic relief without targeting the root causes of OA, making their benefits less substantial and long-term than those of surgical options. For this reason, current non-surgical options are mostly limited to early-stage OA symptomatic management.[10,17]

Considering the major limitations regarding current surgical and non-surgical options, an ideal OA treatment would provide the long-term, substantial benefits of surgery in a non-invasive, lower-cost form, bypassing surgical barriers to allow for earlier OA intervention while still providing treatment that is beyond temporary symptomatic relief. This approach would avoid the high costs and risks associated with surgical options—therefore improving OA treatment accessibility—while still offering a level of clinical efficacy comparable to surgery.

Innovation of Distraction-Unloader Knee Braces

Of the current non-surgical OA options, knee braces are highly regarded due to their fully external, easily customizable, and manufacturable designs. Knee braces are already used as early OA interventional treatments that are significantly cost-effective given continuous wear, slowing OA progression and possibly even avoiding the need for surgery.[2] Furthermore, braces avoid the fundamental aforementioned access barriers that limit surgery, such as the need for operating rooms or anesthesia administration.

Unloader braces show the most promising results compared to other types of braces, such as prophylactic, functional, or compression braces and knee sleeves.[18–20] Traditional unloaders such as the Rebel Reliever (Fig. 2B) use a 3-point unloading system that produces a valgus-directed force in the knee to attempt to reduce medial-compartment joint force.[21] The effectiveness of 3-point unloaders is debated and has not shown clinically significant improvements in patient

Fig. 2. Unloader knee brace designs. (A) OdrA distraction-unloader;[25] (B) Rebel Reliever 3-point unloader®;[21] (C) Adonis® distraction-unloader[26]

outcomes.[22] A novel class of knee brace called distraction-unloaders has been created to distract—or gently separate—the knee's medial compartment by generating an axial unloading force. The medial compartment is targeted as it bears much more force than the lateral compartment and is more commonly impacted by OA.[5,6] The Adonis® distraction-unloader by Icarus Medical works by using geared hinges that increase in radii as the brace straightens into extension, which causes the brace to impart an axially-directed force away from the knee's center on the side where the distraction hinge is applied. It is known that surgical joint distraction, which follows a similar mechanism where rods are used to axially separate the knee joint space, significantly improves pain, joint-space width, and can even encourage cartilage regrowth, slowing OA progression.[9] As such, our goal is to optimize the Adonis® distraction-unloader knee brace design and assess whether these braces can noninvasively provide benefits similar to distraction surgery.

We identified several key limitations in knee brace development that shaped our three capstone aims. First, there is a lack of high-quality, long-term clinical trials to solidify the efficacy of unloader knee braces.[23,24] The unclear clinical evidence largely stems from the absence of standardized brace design guidelines, making it difficult to compare trials that test braces with different designs. For example, Gueugnon et al.[25] and Thoumie et al.[21] conducted randomized-controlled trials on the OdrA and the Rebel Reliever® knee braces, respectively. However, these braces have drastically different designs that confound direct comparison—for example, is it better to have minimized surface area like the OdrA brace (Fig. 2A), or to have four large, supportive straps like the Rebel Reliever® brace (Fig. 2B)? Neither study justifies their design choices, which highlights the need for a more rigorous investigation of unloader knee brace designs to identify which features most effectively unload the medial compartment and produce better clinical outcomes.

We will specifically investigate the Adonis® distraction-unloader knee brace design (Fig. 2C) from Icarus Medical, a medical device company headquartered in Charlottesville, Virginia. Current 3-point unloaders, which horizontally apply force to unload the knee's medial compartment, have the increased risk of overloading the lateral compartment in exchange.[20] In contrast, distraction-unloader knee braces like the Adonis® additionally apply vertical forces to the medial compartment, with the suggested benefit of distributing less force onto the lateral compartment.

Aim 1: Designing an improved clip system.

The current Adonis® brace has four straps with four separate, unlabeled clips (Fig. 2C). The topmost and bottommost straps are worn tightly around the thigh and upper calf, respectively, while the two innermost straps cross each other to provide unloading. Having separate clips for each strap enhances the brace's flexibility and range of motion. However, the high number of clips on the device and the complex strap system make the brace difficult to put on correctly. This complexity is problematic, as ease of use significantly influences whether a patient will continue with a self-administered treatment.[19,27] As such, simplifying the brace's user configuration is a high priority.

Many design alterations were explored, including labeled clips and clips coded by color, shape, or texture. The design adjustment we focused on was creating a merged clip system that maintains the four straps but only has two clips. Multiple factors informed the new system: aesthetics, practicality, and flexibility. In terms of aesthetics, prime considerations were symmetry and ergonomic fit with the brace body. Practical necessities were sufficient clip strength to hold the increased load of two straps, correct dimensions for the strap slots, compatibility with the connector nub, and the ability to be produced within Icarus' existing design infrastructure. Another chief consideration was the clip's ability to slightly rotate to accommodate changes in patient posture and stride. Moreover, working within Icarus' established production capabilities was an

important factor, as we did not want to add to the manufacturing complexity or cost of the brace.

Aim 2: Building a biomechanical knee model.

Quantitative measurement of medial compartment unloading is a key metric for assessing distraction-unloader efficacy. Although medial loading can be estimated in live patients using proxy variables such as the knee adduction moment,[20,28] it is preferable to directly measure the intra-compartmental forces, which can be accomplished using cadavers or biomechanical knee models.[29] To circumvent the safety and logistical limitations of cadaver trials, we prototyped a realistic knee model capable of measuring forces within the medial and lateral compartments. We evaluated the knee model's physiological accuracy by testing for several expected biomechanical outcomes, including the medial compartment bearing more weight than the lateral.

The first step in generating this model was creating a force-sensing circuit that can accurately measure applied force. Once the circuit was calibrated, it was inserted inside a 3D-printed knee model. The original model only recapitulated the tibia and the femur to test the feasibility of building a knee model. Then, a new model was created to represent the bones, ligaments, and menisci. In future work, the knee model can be upgraded to a full leg model, eventually being set in a leg-shaped silicone mold that can wear braces to test different brace design configurations (Fig. S1).

Aim 3: Creating a clinical trial on knee bracing.

We submitted a single-arm prospective clinical trial to evaluate the Adonis® distraction-unloader knee brace's effects on medial compartment OA patients. Though a randomized-controlled trial would have offered a higher level of evidence, a single-arm trial was selected due to limited patient availability and the absence of a standard-of-care brace that could be used to control for the Adonis® brace.

After conducting a literature review, we found that previous OA brace trials mainly assessed efficacy through patient-reported outcome measures (PROMs) like the Knee Injury & Osteoarthritis Outcome Score (KOOS)[25,30] for quality of life and the Visual Analog Scale (VAS) for pain.[21,25] As ease of use is an important focus, we added the Orthotics & Prosthetics Users Survey (OPUS)[31] to track user convenience. To account for confounding factors, questions tracking patient compliance and the use of analgesics or intra-articular injections were added. We varied response formats (e.g., multiple choice, slider bars, etc.) to reduce survey fatigue and attention checks to ensure response accuracy (Table S2).

Biomechanically-focused brace trials use gait analysis to assess if the brace improved leg functionality, collecting spatiotemporal parameters like gait speed, gait symmetry, and stride length before and during brace use. An additional factor we added is knee adduction moment, a common proxy variable for medial compartment loading for live patients.[20,28] Since no suitable clinical gait labs were available near the Charlottesville area, we set up a collaborative analysis study with Dr. Dan Syrett from the Virginia Commonwealth University (VCU) Physical Therapy Department in Richmond. The VCU gait lab will follow the same timeline as our UVA study, administering PROMs and gait analysis at baseline brace fitting and at 1, 2, 4, and 6 weeks post-fitting. De-identified data will be sent to us to assess correlations between PROMs and gait metrics over time. For example, we could analyze whether improved VAS pain scores correlate with improved gait symmetry. The Timed Up-and-Go Test, 6-Minute Walk Test,[32] and Berg Balance Scale[33] were added as common standardized methods for assessing patient gait and lower-limb capacity.

In addition to PROMs like KOOS and VAS, surgical distraction trials often measure efficacy using imaging metrics such as knee joint-space width.[9,34] Ultrasound imaging was chosen as a lower-risk, lower-cost alternative to radiographic imaging, as ultrasound is still capable of reliably measuring knee joint-space width, which can serve as a surrogate measure for cartilage thickness. Increased knee joint-space width is associated with decreased OA severity and better knee functional outcomes. Imaging will occur only at baseline and 6 weeks post-fitting.[35]

Regarding statistical analysis, the Friedman test will check for significant PROM score changes over time, followed by a post-hoc Nemenyi test for pairwise time point comparisons if significance is found.[36] A linear mixed effects regression model will analyze PROM trajectories, treating time as a fixed effect to track trends, and patient compliance and demographic factors as fixed effects to control for inter-subject

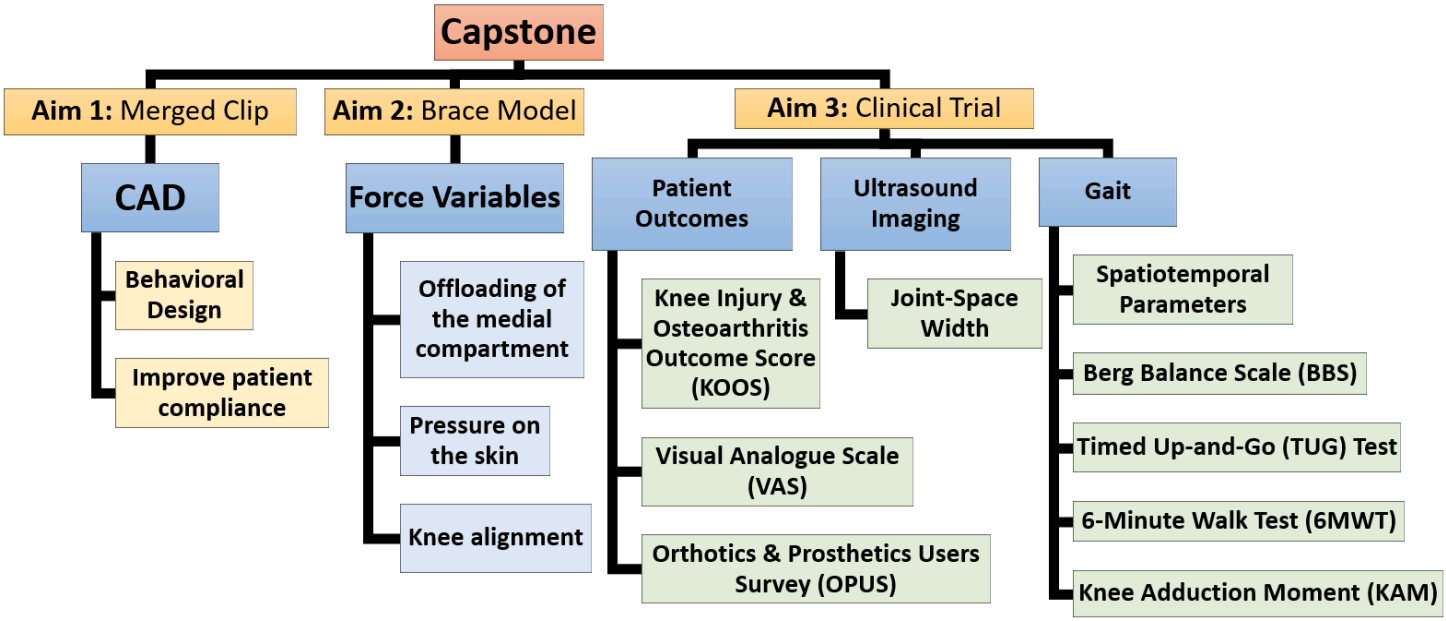

Fig. 3. Key capstone aims and variables. Our investigation of the Adonis® knee brace focused on its behavioral design and user configuration (Aim 1), biomechanical model measurements (Aim 2), and clinical efficacy (Aim 3).

variability.[37] Mixed model ANOVAs will assess changes in gait metrics and joint-space width over time.[38] Multiple correlation analysis will explore relationships between PROMs, imaging, and gait metric outcomes.[39]

In summary, we developed a single-arm prospective clinical trial incorporating subjective and objective metrics, including PROMs to assess quality of life and pain, imaging to measure joint-space width, and gait analysis to evaluate leg functionality. The study is a collaboration between the UVA Department of Biomedical Engineering, Icarus Medical, UVA Health Prosthetics & Orthotics (with orthotist Max Ronkos), the VCU Department of Physical Therapy (with Dr. Dan Syrett), and the UVA Orthopedic Surgery Department (with Dr. Wendy Novicoff, serving as principal investigator, and Eric McVey, serving as clinical trial coordinator). The clinical trial is currently awaiting full-board Institutional Review Board (IRB) approval. All key variables are summarized in Fig. 3.

Materials and Methods

Materials

The distraction-unloader brace used was the Adonis® brace from Icarus Medical, which is headquartered in Charlottesville, Virginia. The materials used for 3D printing were nylon, polylactic acid (PLA), and thermoplastic polyurethane (TPU) at 85 Shore A, which is roughly the hardness of a leather belt.[40] PLA at a 10% infill was used to 3D-print the bones of the first knee model. Solid nylon was used for the bones in the final knee model, while TPU was used to print the ligaments and cartilage. The force-measuring sensor procured from DFRobot was the 0.5" Force Sensitive Resistor, with the capacity to measure from 100g–10kg (Model: SEN0047).[41] The microcontroller used for the force-sensing circuit was an Arduino Uno from the Vilros Basic Starter Kit.[42]

Methods

Prototypes 3D-printed in PLA were manufactured using fused deposition modeling (FDM) printers at the UVA Scholars' Lab Makerspace. Prototypes generated in nylon were printed at Icarus with selective laser sintering (SLS) 3D printers. A simple voltage divider circuit was used to output raw data (Fig. S3). A 10 kΩ pull-down resistor was connected in series with the force sensitive resistor. A 5V input was used. To gather data from the force-sensing circuit, a program was written in Arduino IDE (Fig. S4). The raw output from the circuit at these levels was a conductance value in μMhos that is directly proportional to the force being applied throughout the sensor's linear 100g–10kg loading range. To calibrate the circuit, a series of exercise weights were placed atop a 0.5" diameter button pressing down on the force sensitive resistor. The corresponding conductance levels were

measured at these weights at a sampling rate of 100 Hz. The ratio of actual weight applied to conductance level was computed for each condition and the average of all ratios was taken and found to be 0.0118 lbf/µMhos (Fig. 4A). This conversion factor was implemented in the Arduino code to directly output the data in lbf. Testing the circuit with known weights confirmed the accuracy of the outputted force data (Fig. 4B).

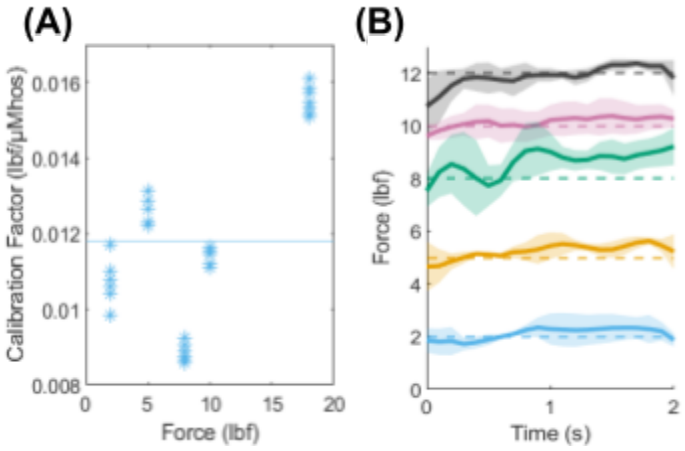

Fig. 4. Calibration factor and testing. (A) Exercise weights (2, 5, 8, 10, 18 lbs) were loaded to generate a conversion factor (solid line) to transfer the data from µMhos to lbf (n=6). (B) The circuit accurately recapitulated the applied force (dashed line) over a range of weights. Shaded areas indicate standard deviation (n=3).

Results

Aim 1: Merged clip-strap system.

The merged clip system was iterated on and improved to create an aesthetically pleasing, functional prototype (Fig. S5). Qualitative testing revealed that brace comfort and strap range of motion were restricted by the new design (Fig. S6). Because two straps are attached to the same clip, the ability of the straps to rotate independently of each other was hindered. Strap rotation is a minor but important facet of the brace design: normally, the crossed inner straps exhibit small rotations throughout the range of knee motion, while the uppermost and bottommost straps barely rotate at all. Thus, by fixing the stationary straps to the rotating straps using a rigid clip, the brace's range of motion, fit, and comfort are compromised.

Aim 2: Biomechanical knee model.

We designed two iterations of a biomechanical knee model to measure the force on the medial compartment throughout the range of motion. The bones of our model are based on a freely available computed tomography (CT) scan of a right knee from a human male, found on GrabCAD.[43] Accurately capturing the force on the medial compartment requires reproducing the bony topography of the tibial and femoral contact surfaces within the knee. To preserve the curvy bone contact surfaces while still using our flat sensor, we made cutouts beneath the medial and lateral compartments where the sensor can lie flat and added a sensor cap that has a 0.5" diameter cylindrical actuator to press down on the sensing surface.

The initial model consisted of a femur section, a tibia section with a medial cutout, and a medial sensor cap (Fig. 5A). That model was used for proof of concept and circuit troubleshooting before moving to a more advanced model. The final model, made of solid nylon, had the femur and tibia with cutouts for both the medial and lateral compartments (Fig. 5B). Additionally, it had removable meniscal cartilage and ligaments printed in TPU. Ligament dimensions were gathered from literature but altered to fit the knee model. As our design goal was to replicate basic passive resistance and hold the model in place using the ligaments, printing the complex design of every ligament was unnecessary. The ligament system was simplified down to the two side ligaments and the posterior cruciate ligament. Ligaments were printed in TPU with premade holes to avoid tearing the grain upon screwing them onto the nylon model. The knee model was loaded by placing exercise weights on top of the femur (Fig. S7).

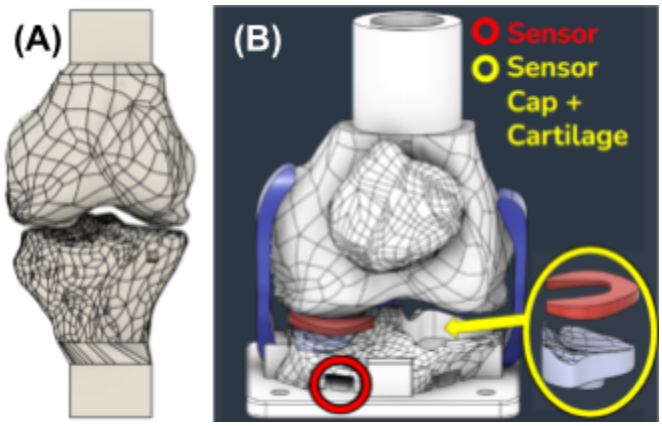

Fig. 5. Knee model prototypes. (A) Initial bones-only model; (B) Model with bones, cartilage, and ligaments.

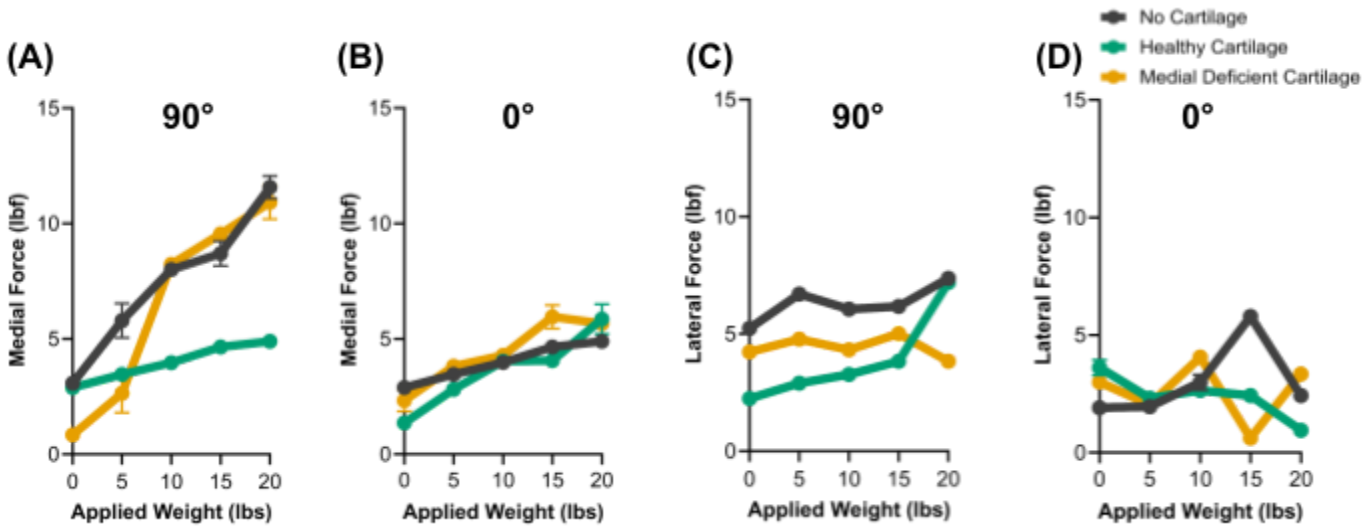

Fig. 6. Vertical (90°) and horizontal (0°) loading of the medial and lateral compartments. Vertical loading of the medial compartment (A) showed higher medial force than horizontal loading (B). Vertical loading of the lateral compartment (C) showed higher medial force than horizontal loading (D) (n=3).

Three cartilage conditions were tested: no cartilage; healthy cartilage, which included both the medial and lateral pieces; and medial deficient cartilage, in which only the lateral cartilage piece was inserted. When unloaded, the medial compartment registered a base force reading of around 3 lbf in the vertical and horizontal positions (Fig. 6A–B). This baseline loading is created by the static weight of the femur piece and the compressive tension generated by the ligaments.

Vertical loading demonstrated that the medial compartment was subjected to more than 50% of the loading for each tested weight in the no cartilage and medial deficient groups at an average of 78.0% and 63.4% of total loading, respectively. The medial compartment bearing the majority of the weight aligns with our expected results for a physiologically accurate knee model, as the medial compartment usually bears 60–80% of the weight compared to the lateral compartment in real human knees.[5,6] All cartilage groups exhibited a positive trend in the medial compartment as the applied weight increased for both the vertical and horizontal positions (Fig. 6A–B). Notably, while the healthy cartilage condition force readings increased linearly with added weight, the sensor only registered small increases in force and 37% of the total weight that was actually applied, possibly due to the menisci being too big for the sensor caps.

For vertical loading conditions more than 10 lbs, the medial compartment forces for the no cartilage and medial deficient conditions were closely aligned. We expected the absence of a medial meniscus to result in greater medial loading than the no cartilage condition, but our model did not verify this. A likely explanation is that the side ligaments were too stiff to permit slightly varus alignment, meaning that the side ligaments prevented the femur from tilting and transferring more force onto the medial compartment for the medial deficient condition.

The lateral compartment was also tested with vertical and horizontal loading (Fig. 6C–D). In vertical loading, there appears to be a gentle upward trend for each cartilage condition. We expected to see an upward trend wherein each point is less than 50% of the total applied weight. However, there is more variability with the lateral data than in the medial data, suggesting testing and alignment errors. In horizontal loading, the data were sporadic and generally trended in a flat line.

Using data from the vertical loading trials, we summed the averaged force readings from the medial and lateral compartments to compare the total weight detected with the actual total weight applied (Fig. 7). Regardless of cartilage presence, we expected the combined sensor readings to capture 100% of the total weight applied, indicating effective force transmission to the knee's sensors. However, some variability is expected, especially because baseline readings consistently showed nonzero values—typically under 5 lbf—due to the femur's weight and ligament tension. This analysis revealed that the healthy cartilage condition offloaded force onto non-sensing sections of

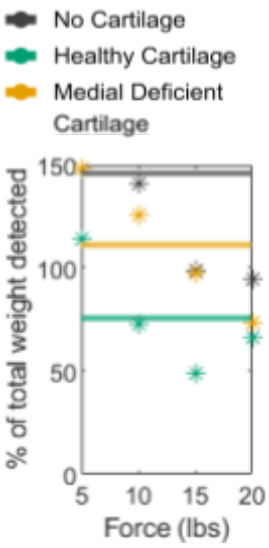

Fig. 7. Comparison of total measured force to known applied force. The no cartilage condition tended to overestimate the applied load, whereas the healthy cartilage condition underestimated it. The medial deficient condition had the closest expected values.

the model, leading to only 75.4% of the total weight being detected, significantly below 100% (Fig. 7). Therefore, the artificial cartilage pieces are redistributing force off the sensing surface, leading to an underestimate. In contrast, the no cartilage condition tended to overestimate at 146.1%, possibly due to the added baseline weight of the model, while the medial deficient condition was closest to the expected value at 111.2% (Fig. 7).

The loading of the medial and lateral compartments over the knee's range of motion was measured by loading the model with 5 lbs and moving the model from 0° to 90° by hand, approximating a constant velocity before more sophisticated test equipment is generated (Fig. S7). Only two cartilage conditions were tested (no cartilage and healthy cartilage) because the medial deficient cartilage version moved too jerkily from 0° to 90° (Fig. 8). In the medial and lateral compartments, the no cartilage condition experienced a strong upward then downward trend, peaking at around 55°. This finding indicates that maximum loading on the medial compartment occurs at 55°; however, we expected the maximum to be at 90°, where the knee alignment is straight and resembles a typical standing position. In the healthy cartilage condition for the medial force graph, the force did not show a strong positive or negative trend over the range of motion. However, for the lateral force graph, there was a consistently shaped curve that bottomed out at about 50° before rising to a peak at 80° (Fig. 8).

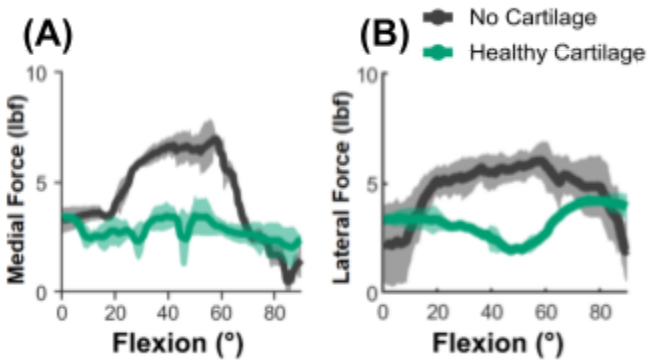

Fig. 8. Measured force from 5 lb loading across the degree of knee flexion. Curves show the change in force in the medial (A) and lateral (B) compartments during loading. Shaded areas indicate standard deviation (n=3).

The reason the range of motion graphs peak at 55° is probably due to our model's ligaments being at their maximum tightness at that point. Problems with the healthy cartilage group included shifting cartilage and overlap with the non-sensing sections of the tibia piece. The vertically-loaded medial compartment did not account for more than 50% of the total weight in the healthy cartilage condition because the cartilage distributed weight onto the non-sensing surfaces of the knee. Adjusting the menisci and making the test conditions more uniform will assuage this problem.

Furthermore, the lateral compartment failed to show increased vertical loading as more weight was added because the sensor was being pushed at an angle rather than straight down. The sensor cap was observed slipping out of vertical alignment due to the contact point of the femur pressing on the edge of the sensor cap instead of the center, causing the cap to be slightly uprooted. We believe the sporadicity of the data in the lateral compartment horizontal condition is also caused by the same reasons. As such, to improve the accuracy of the data outputs, there must be consistent, strong contact with the central sensing area.

Aim 3: Single-arm prospective clinical trial.

A comprehensive literature review of current OA treatments was conducted to inform the need for the clinical trial. A protocol was generated and submitted for IRB review. However, changes in study type and principal investigator slowed the approval process, so clinical data have not yet been gathered.

Discussion

Aim 1: Behavioral design and user configuration.

Because the brace's physical structure is directly linked to its functionality, structural design changes can impact efficacy. Our merged clip brace improved ease of use but limited the brace's range of motion. As a result, Icarus design engineers weighed the options of a simpler two-clip system with limited motion or a four-clip

system with reduced user convenience. As brace efficacy and functionality are higher priorities, Icarus decided to keep the four-clip design. Usability will instead be improved through a combination of clip color-coding, shape-coding, and labeling.

Aim 2: Mechanically measuring the internal unloading effects of knee braces.

We created a promising knee model that established proof of concept for near-instantaneous force measurements in the medial and lateral compartments. Eventually, future iterations of the model can test the Adonis® brace's effectiveness in unloading the medial compartment and its impact on the lateral compartment.

Multiple current shortcomings in our model can be addressed in the next iteration. First, the knee's menisci overlap onto non-sensing sections of the tibia because they are too big for the current tibial sensor caps. This overlap can be resolved by changing the shape of the menisci, adhering the menisci to the femoral or tibial surface, or turning the sensor caps into the entire top of the tibial surface with a central divide to demarcate the medial and lateral sections. Second, the roughness of the femoral and meniscal surfaces generates too much friction, which causes bumpy and uneven movement when attempting to load the knee and test its range of motion. Jerky movement can be mitigated by smoothing the femoral surface or by adding a thin, smooth cartilage cap over the femoral surface, which would reduce friction as well as increase the femur's physiological accuracy.[29] Third, the tibial sensor cap cutouts move around too much, which causes misalignment and uneven sensor loading. This misalignment problem can be solved by making the sensor caps fit even tighter within the tibia by reducing the clearance width between the sensor caps and the cutouts they slot into. Additionally, the cap's height and the cutout's depth can be increased. These changes will prevent the caps from shifting and keep the forces on the sensor vertical, such that more of the applied force is properly reaching the force-sensing resistors.

Multiple improvements can be made in future iterations. The ligaments can be adjusted so they are more physiologically accurate in terms of their spring constants and shape. The ligaments only account for passive resistance. A potential solution for adjusting ligament tension is using rubber bands to represent or fine-tune ligaments.[29] It would be useful to add features to the knee model that represent the active resistance from dynamic muscle movement through the knee's range of motion.

Once the knee model's physiological accuracy and functionality are optimized, it can be upgraded to a full-leg model encased in silicone to test different brace designs. Aside from observing the Adonis® brace's impact on medial and lateral compartment loading, there are many other testing possibilities. For example, it would be useful to compare the Adonis® against other distraction-unloaders like the OdrA brace[25] to assess which design features are most helpful in a distraction-unloader (e.g., number of straps, brace thickness, etc.), which will inform future design adjustments and brace optimization.

Aim 3: Challenges in achieving high-quality clinical trials and design standardization.

Navigating the clinical trial development and approval process revealed several key insights. First, the lack of high-quality knee brace trials may stem less from poor trial design and more from broader issues such as limited funding, small patient pools, and the absence of standardized brace designs—making it difficult to establish a standard-of-care control or compare findings across trials. This lack of brace design guidelines is particularly problematic, as it has resulted in an overwhelming variety of brace designs with little guidance on which brace features work best. As such, future trials would benefit from writing clearer design justifications or adding comparative groups. For example, there could be one group that has a four-strap brace and another with a two-strap brace to inform ideal strap configuration.

Braces must be consistently worn over time for maximum effectiveness, which necessitates longitudinal trials. However, the need for a long treatment duration introduces more confounding factors, as OA patients often partake in many other concurrent therapies to alleviate their symptoms, such as analgesics, physical therapy, and intra-articular injections. Even daily activities such as soaking in a warm bath may temporarily reduce OA symptoms and therefore affect patient performance-based outcomes such as PROMs or gait. Also, as OA is a degenerative disease, its symptoms often progressively worsen, which conflicts with

assessing true brace efficacy in longitudinal analyses. Finally, the long-term and self-administered nature of braces makes patient compliance a major concern. As such, it is recommended for patient compliance, concurrent therapies, daily activities, and OA disease progression to be carefully monitored throughout long-term brace trials. Adding outcomes that are not based on patient performance, such as imaging, would also be helpful.

Given the broader goal of developing effective alternatives to surgery for knee OA, future clinical trials should compare bracing and surgical outcomes. For example, a trial that includes patients who add a distraction-unloader to their treatment regimen, patients who continue with their usual care, and patients who undergo surgical distraction would help clarify how distraction-unloaders compare to other non-surgical options and surgical distraction.

End Matter

Author Contributions and Notes

Mira Zineddin and Anna Dugan designed the specific aims and performed the research, including collaborating on the merged clip-brace design, biomechanical knee model design and testing, the clinical trial submission, and writing the paper. Dave Johnson and Cole Yantiss provided design and testing input. Max Ronkos provided consultation on the clinical trial and biomechanical model construction.

Mira Zineddin and Anna Dugan declare no conflicts of interest. Max Ronkos is a clinical consultant for the study's sponsor, Icarus Medical, and received less than $5,000 in the past year. Dave Johnson and Cole Yantiss are current or former employees who received more than $10,000 per year from Icarus Medical.

Acknowledgements

Funding for this project was provided by Icarus Medical. Thank you to Dave Johnson, Cole Yantiss, Evan Eckersley, and Philip Miller from Icarus Medical, as well as Max Ronkos from UVA Health Prosthetics & Orthotics for serving as crucial mentors. Thank you to Dr. Wendy Novicoff from the UVA Orthopedic Surgery Department for serving as the principal investigator and Eric McVey for serving as the clinical research coordinator. Thank you to Dr. Dan Syrett from the VCU Department of Physical Therapy for agreeing to a collaborative analysis study. Thank you to Dr. David Martin from the UVA Health Library Sciences Data Services department for assisting with the clinical trial statistical analysis plan. Finally, thank you to Dr. Timothy Allen, Mario Garcia, and Timothy Ho for their teaching and support throughout the research.

References

1. Ciapini G, Simonettii M, Giuntoli M, et al. Is the Combination of Platelet-Rich Plasma and Hyaluronic Acid the Best Injective Treatment for Grade II-III Knee Osteoarthritis? A Prospective Study. *Adv Orthop*. 2023;2023:1868943. doi:10.1155/2023/1868943

2. Lee PY, Winfield TG, Harris SR, Storey E, Chandratreya A. Unloading knee brace is a cost-effective method to bridge and delay surgery in unicompartmental knee arthritis. *BMJ Open Sport Exerc Med*. 2017;2(1). doi:10.1136/bmjsem-2016-000195

3. Lespasio MJ, Piuzzi NS, Husni ME, Muschler GF, Guarino A, Mont MA. Knee Osteoarthritis: A Primer. *Perm J*. 2017;21(4):16-183. doi:10.7812/TPP/16-183

4. Long H, Liu Q, Yin H, et al. Prevalence Trends of Site-Specific Osteoarthritis From 1990 to 2019: Findings From the Global Burden of Disease Study 2019. *Arthritis Rheumatol*. 2022;74(7):1172-1183. doi:10.1002/art.42089

5. Segal NA. Bracing and Orthoses: A Review of Efficacy and Mechanical Effects for Tibiofemoral Osteoarthritis. *PM&R*. 2012;4(5S):S89-S96. doi:10.1016/j.pmrj.2012.01.018

6. Stoddart JC, Dandridge O, Garner A, Cobb J, Arkel RJ van. The compartmental distribution of knee osteoarthritis – a systematic review and meta-analysis. *Osteoarthritis Cartilage*. 2021;29(4):445-455. doi:10.1016/j.joca.2020.10.011

7. Petersen W, Ellermann A, Henning J, et al. Non-operative treatment of unicompartmental osteoarthritis of the knee: a prospective randomized trial with two different braces-ankle-foot orthosis versus knee unloader brace. *Arch Orthop Trauma Surg*. 2019;139(2):155-166. doi:10.1007/s00402-018-3040-8

8. Math KR, Zaidi SF, Petchprapa C, Harwin SF. Imaging of Total Knee Arthroplasty. *Semin Musculoskelet Radiol*. 2006;10:047-063. doi:10.1055/s-2006-934216

9. van der Woude JAD, Wiegant K, van Heerwaarden RJ, et al. Knee joint distraction compared with high tibial osteotomy: a randomized controlled trial. *Knee Surg Sports Traumatol Arthrosc*. 2017;25(3):876-886. doi:10.1007/s00167-016-4131-0

10. McCormack DJ, Puttock D, Godsiff SP. Medial compartment osteoarthritis of the knee: a review of surgical options. *EFORT Open Rev*. 2021;6(2):113-117. doi:10.1302/2058-5241.6.200102

11. Vina ER, Cloonan YK, Ibrahim SA, Hannon MJ, Boudreau RM, Kwoh CK. RACE, GENDER AND TOTAL KNEE REPLACEMENT CONSIDERATION: THE ROLE OF SOCIAL SUPPORT. *Arthritis Care Res*. 2013;65(6):969-976. doi:10.1002/acr.21926

12. Hartnett DA, Lama CJ, Brodeur PG, Cruz AI, Gil JA, Cohen EM. Socioeconomic Disparities in the Utilization of Total Knee Arthroplasty. *J Arthroplasty*. 2022;37(10):1973-1979.e1. doi:10.1016/j.arth.2022.04.033

13. Zhang L, Lix LM, Ayilara O, Sawatzky R, Bohm ER. The effect of multimorbidity on changes in health-related quality of life following hip and knee arthroplasty. *Bone Jt J*. 2018;100-B(9):1168-1174. doi:10.1302/0301-620X.100B9.BJJ-2017-1372.R1

14. Ghomrawi HMK, Mushlin AI, Kang R, et al. Examining Timeliness of Total Knee Replacement Among Patients with Knee Osteoarthritis in the U.S. *J Bone Joint Surg Am*. 2020;102(6):468-476. doi:10.2106/JBJS.19.00432

15. Perdisa F, Bordini B, Salerno M, Traina F, Zaffagnini S, Filardo G. Total Knee Arthroplasty (TKA): When Do the Risks of TKA Overcome the Benefits? Double Risk of Failure in Patients up to 65 Years Old. *Cartilage*. 2023;14(3):305. doi:10.1177/19476035231164733

16. Jette DU, Hunter SJ, Burkett L, et al. Physical Therapist Management of Total Knee Arthroplasty. *Phys Ther*. 2020;100(9):1603-1631. doi:10.1093/ptj/pzaa099

17. DeRogatis M, Anis HK, Sodhi N, et al. Non-operative treatment options for knee osteoarthritis. *Ann Transl Med*. 2019;7(Suppl 7):S245. doi:10.21037/atm.2019.06.68

18. Paluska SA, Mckeag DB. Knee Braces: Current Evidence and Clinical Recommendations for Their Use. *Am Fam Physician*. 2000;61(2):411-418.

19. Dzidotor GK, Jeffrey B Moorhead J, Ude CC, Ogueri KS, Ghosh D, Laurencin CT. Functions and Effectiveness of Unloader, Patellofemoral, and Knee Sleeve Orthoses: A Review. *Regen Eng Transl Med*. 2023;10(2):147. doi:10.1007/s40883-023-00313-1

20. Parween R, Shriram D, Mohan RE, Lee YHD, Subburaj K. Methods for evaluating effects of unloader knee braces on joint health: a review. *Biomed Eng Lett*. 2019;9(2):153. doi:10.1007/s13534-019-00094-z

21. Thoumie P, Marty M, Avouac B, et al. Effect of unloading brace treatment on pain and function in patients with symptomatic knee osteoarthritis: the ROTOR randomized clinical trial. *Sci Rep*. 2018;8(1):10519. doi:10.1038/s41598-018-28782-3

22. Gohal C, Shanmugaraj A, Tate P, et al. Effectiveness of Valgus Offloading Knee Braces in the Treatment of Medial Compartment Knee Osteoarthritis: A Systematic Review. *Sports Health*. 2018;10(6):500-514. doi:10.1177/1941738118763913

23. Beaudreuil J, Bendaya S, Faucher M, et al. Clinical practice guidelines for rest orthosis, knee sleeves, and unloading knee braces in knee osteoarthritis. *Joint Bone Spine*. 2009;76(6):629-636. doi:10.1016/j.jbspin.2009.02.002

24. Mistry DA, Chandratreya A, Lee PYF. An Update on Unloading Knee Braces in the Treatment of Unicompartmental Knee Osteoarthritis from the Last 10 Years: A Literature Review. *Surg J*. 2018;4(3):e110. doi:10.1055/s-0038-1661382

25. Gueugnon M, Fournel I, Soilly AL, et al. Effectiveness, safety, and cost-utility of a knee brace in medial knee osteoarthritis: the ERGONOMIE randomized controlled trial. *Osteoarthritis Cartilage*. 2021;29(4):491-501. doi:10.1016/j.joca.2020.11.009

26. Adonis. Icarus Medical. 2025. Accessed May 3, 2025. https://icarusmedical.com/adonis/

27. Bashir AZ, Dinkel DM, Pipinos II, Johanning JM, Myers SA. Patient Compliance With Wearing Lower Limb Assistive Devices: A Scoping Review. *J*

Manipulative Physiol Ther. 2022;45(2):114. doi:10.1016/j.jmpt.2022.04.003

28. Petersen W, Ellermann A, Zantop T, et al. Biomechanical effect of unloader braces for medial osteoarthritis of the knee: a systematic review (CRD 42015026136). *Arch Orthop Trauma Surg*. 2016;136(5):649-656. doi:10.1007/s00402-015-2388-2

29. Paci JM, Scuderi MG, Werner FW, Sutton LG, Rosenbaum PF, Cannizzaro JP. Knee Medial Compartment Contact Pressure Increases with Release of the Type I Anterior Intermeniscal Ligament. *Am J Sports Med*. 2009;37(7):1412-1416. doi:10.1177/0363546509331418

30. Roos EM, Lohmander LS. The Knee injury and Osteoarthritis Outcome Score (KOOS): from joint injury to osteoarthritis. *Health Qual Life Outcomes*. 2003;1:64. doi:10.1186/1477-7525-1-64

31. Peaco A, Halsne E, Hafner BJ. Assessing Satisfaction With Orthotic Devices and Services: A Systematic Literature Review. *JPO J Prosthet Orthot*. 2011;23(2):95. doi:10.1097/JPO.0b013e318217a0fe

32. Dobson F, Hinman RS, Roos EM, et al. OARSI recommended performance-based tests to assess physical function in people diagnosed with hip or knee osteoarthritis. *Osteoarthritis Cartilage*. 2013;21(8):1042-1052. doi:10.1016/j.joca.2013.05.002

33. Hatfield GL, Morrison A, Wenman M, Hammond CA, Hunt MA. Clinical Tests of Standing Balance in the Knee Osteoarthritis Population: Systematic Review and Meta-analysis. *Phys Ther*. 2016;96(3):324-337. doi:10.2522/ptj.20150025

34. Intema F, Roermund PMV, Marijnissen ACA, et al. Tissue structure modification in knee osteoarthritis by use of joint distraction: an open 1-year pilot study. *Ann Rheum Dis*. 2011;70(8):1441. doi:10.1136/ard.2010.142364

35. Zhu J, Li B, Qiu L, et al. A measurement method of knee joint space width by ultrasound: a large multicenter study. *Quant Imaging Med Surg*. 2020;10(5):979-987. doi:10.21037/qims-20-373

36. Pereira D, Afonso A, Medeiros F. Overview of Friedman's Test and Post-hoc Analysis. *Commun Stat - Simul Comput*. 2015;44(10):2636-2653. doi:https://doi.org/10.1080/03610918.2014.931971

37. Schober P, Vetter TR. Linear Mixed-Effects Models in Medical Research. *Anesth Analg*. 2021;132(6):1592. doi:10.1213/ANE.0000000000005541

38. Murrar S, Brauer M. Mixed Model Analysis of Variance. In: *The SAGE Encyclopedia of Educational Research, Measurement, and Evaluation*. 1st ed. SAGE Publications, Inc.; 2018:1075-1078. http://dx.doi.org/10.4135/9781506326139.n436

39. Miot HA. Correlation analysis in clinical and experimental studies. *J Vasc Bras*. 2018;17(4):275-279. doi:10.1590/1677-5449.174118

40. All About the Shore A Hardness Scale. Accessed May 3, 2025. https://www.xometry.com/resources/materials/shore-a-hardness-scale/

41. 0.5" Force-Sensitive Resistor (SKU:SEN0047). DFRobot. Accessed May 6, 2025. https://wiki.dfrobot.com/Force_Sensitive_Resistor_0.5___SKU_SEN0047_

42. Vilros Basic Starter Kit for Arduino Uno R3 | vilros.com | Free Shipping. Vilros. Accessed May 6, 2025. https://vilros.com/products/arduino-uno-basic-starter-kit

43. Knee Joint | 3D CAD Model Library | GrabCAD. Accessed May 5, 2025. https://grabcad.com/library/knee-joint-6

Supplemental Figures

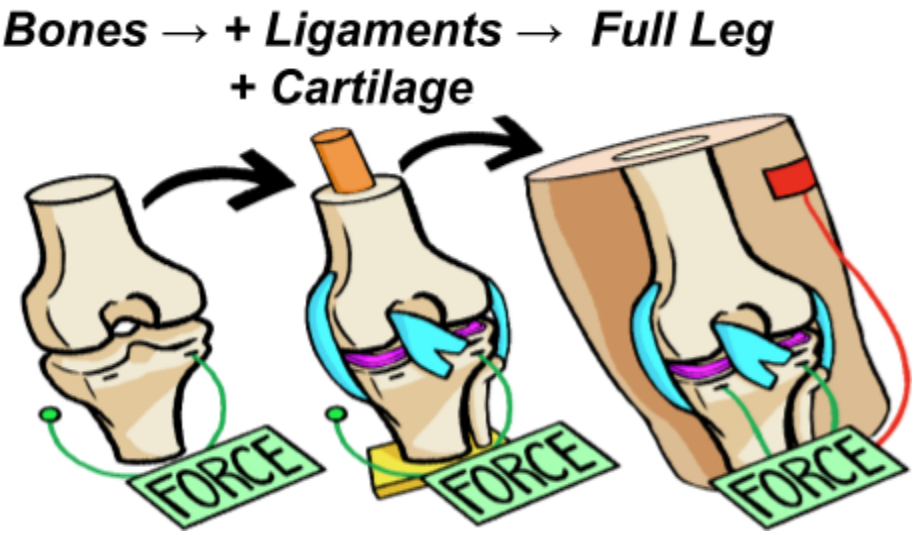

Fig. S1. Silicone leg creation process (Aim 2).

Table S2. Total Knee Orthotic Patient Questionnaire (Aim 3).

Patient Demographics: Social Determinants of Health
Age, gender, race, education level, native language, income bracket, BMI, existing comorbidities

Orthotics & Prosthetics Users Survey (OPUS): Satisfaction with Device and Services

1. My brace fits well
2. The weight of my brace is manageable
3. My brace is comfortable throughout the day
4. It is easy to put on my brace
5. My brace looks good
6. My brace is durable
7. My clothes are free of wear and tear from my brace
8. My skin is free of abrasions and irritations
9. My brace is pain-free to wear

**Results are ranked between 1 (strongly disagree) and 5 (strongly agree). The total OPUS score is 0-100.*

Visual Analog Scale (VAS): Pain
On a scale of 0 to 10 overall, with 0 meaning no pain and 10 meaning the worst imaginable pain, how much knee pain have you experienced in the **past week?**

Patient Compliance Questions:
Since your last appointment, how often do you wear your brace when you are standing or putting pressure on your knee?
**Results are ranked between 1 (rarely) and 5 (always).*

How many days out of the week do you wear your brace?

**Results are ranked between 1-7 days.*

**The patients' attendance records will also be tracked to certify we have all the necessary information for each patient.*

Intra-Articular Injection Questions:

Since your last appointment, have you received any of the following injections? *Yes / No*

- Corticosteroid injection
- Hyaluronic acid injection
- Platelet rich plasma injection
- Stem cell-type injection

(If yes:)

Did the injection noticeably improve your pain levels? *Yes / No*

Did the injection noticeably improve your knee functionality? *Yes / No*

Pain Medication Questions:

Since your last appointment, have you used pain medications such as aspirin, ibuprofen (Advil, Motrin), naproxen (Aleve, Naprosyn), ketoprofen (Orudis), or etodolac (Lodine)? *Yes / No*

(If yes:)

Did the medication noticeably improve your pain levels? *Yes / No*

Did the medication noticeably improve your knee functionality? *Yes / No*

Attention Checks:

**Attention checks will be scattered throughout the questionnaire, such as:*

- To ensure the accuracy of your answers, please select 'Strongly Agree.'
- Please slide the scale bar to '9.5' before clicking Next.

Knee Injury & Osteoarthritis Outcome Score (KOOS): Quality of Life

Patients are asked to rank the following experiences within the **past week:**

Symptoms S1. Do you have swelling in your knee? S2. Do you feel grinding, hear clicking or any other type of noise when your knee moves? S3. Does your knee catch or hang up when moving? S4. Can you straighten your knee fully? S5. Can you bend your knee fully?	*Quality of life* Q1. How often are you aware of your knee problem? Q2. Have you modified your lifestyle to avoid potentially damaging activities to your knee? Q3. How much are you troubled with lack of confidence in your knee? Q4. In general, how much difficulty do you have with your knee?
Stiffness S6. How severe is your knee joint stiffness after first waking in the morning? S7. How severe is your knee stiffness after sitting, lying, or resting later in the day?	*Function, sports, and recreational activities* SP1. Squatting SP2. Running SP3. Jumping SP4. Twisting/pivoting on your injured knee SP5. Kneeling
Pain P1. How often do you experience knee pain? P2. Twisting/pivoting on your knee P3. Straightening knee fully	*Function, daily living* A1. Descending stairs A2. Ascending stairs A3. Rising from sitting

P4. Bending knee fully P5. Walking on a flat surface P6. Going up or down stairs P7. At night while in bed P8. Sitting or lying P9. Standing upright	A4. Standing A5. Bending to floor/pick up an object A6. Walking on flat surface A7. Getting in/out of car A8. Going shopping A9. Putting on socks/stockings A10. Rising from bed A11. Taking off socks/stockings A12. Lying in bed (turning over, maintaining knee position) A13. Getting in/out of bath A14. Sitting A15. Getting on/off toilet A16. Heavy domestic duties (moving heavy boxes, scrubbing floors, etc.) A17. Light domestic duties (cooking, dusting, etc.)

**Almost all results are ranked on a scale of 1 (Never), 2 (Mild), 3 (Moderate), 4 (Severe), 5 (Extreme)*
**Temporal questions:*
- *S1-S5 are ranked on a scale of 1 (Never), 2 (Rarely), 3 (Sometimes), 4 (Often), 5 (Always)*
- *P1 is ranked on a scale of 1 (Never), 2 (Monthly), 3 (Weekly), 4 (Daily), 5 (Always)*

**Quality of life questions:*
- *Q1 is ranked on a scale of 1 (Never), 2 (Monthly), 3 (Weekly), 4 (Daily), 5 (Constantly)*
- *Q2 is ranked on a scale of 1 (Never), 2 (Mildly), 3 (Moderately), 4 (Severely), 5 (Extremely)*

**KOOS score ranges from 0-100, with 0 representing extreme knee dysfunction and 100 representing no knee problems.*

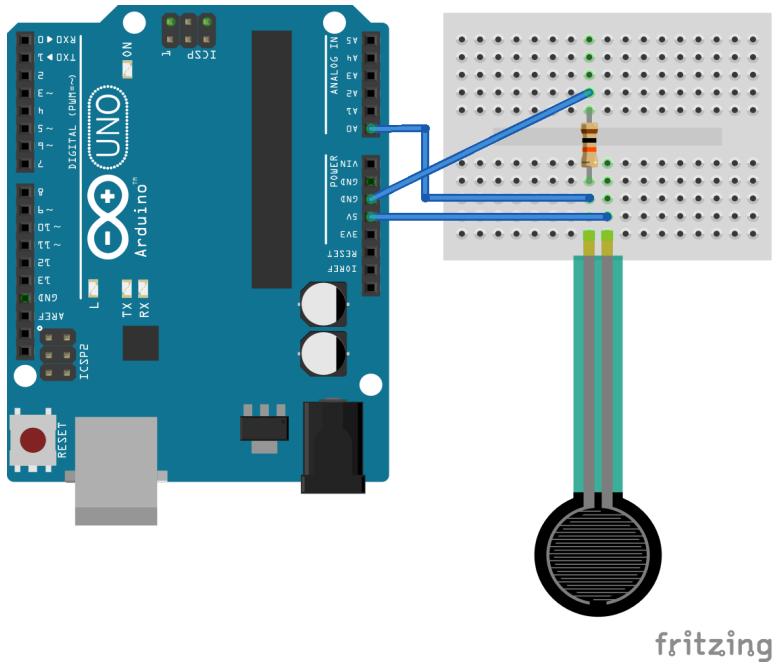

Fig. S3. Circuit schematic and appearance (Aim 2).
Schematic was generated using Fritzing 9.3b.

```
int fsrPin = 0;
int fsrReading;
int fsrVoltage;
float fsrResistance;
float fsrConductance;
float fsrWeight;
void setup(void) {
  Serial.begin(9600);
}
void loop(void) {
  fsrReading = analogRead(fsrPin);
  fsrVoltage = map(fsrReading, 0, 1023, 0, 5000); //5V
  if (fsrVoltage == 0) {
    Serial.print("0 ");
  } else {
    //  Conductance = ((5000 mV - fsrVoltage) * fsrResistance) / fsrVoltage
    fsrResistance = 5000 - fsrVoltage;     // 5000mV
    fsrResistance *= 10000;                // 10K
    fsrResistance /= fsrVoltage;
    fsrConductance = 1000000;           // microMhos
    fsrConductance /= fsrResistance;
    fsrWeight = fsrConductance *0.0118; // lbf/microMhos; //conversion factor
    Serial.print(fsrWeight);
    Serial.print(" ");
  }
  delay(10);
}
```

Fig. S4. Arduino code (Aim 2).

(A) Original clip **(B)** Early prototype clip **(C)** Late prototype clip **(D)** 3D-printed prototype

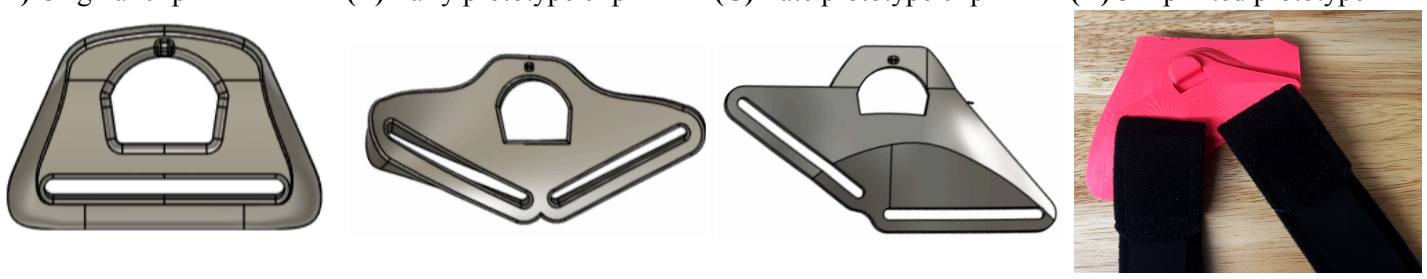

Fig. S5. Merged clip designing and printing (Aim 1). The original clip with one strap slot (A) compared to an early prototype clip design with two strap slots (B) and a prototype with improved contour (C). Prototypes were 3D-printed with polylactic acid (PLA) and tested to ensure compatibility with the brace's existing strap system.

Fig. S6. Fully merged clip brace design (Aim 1).

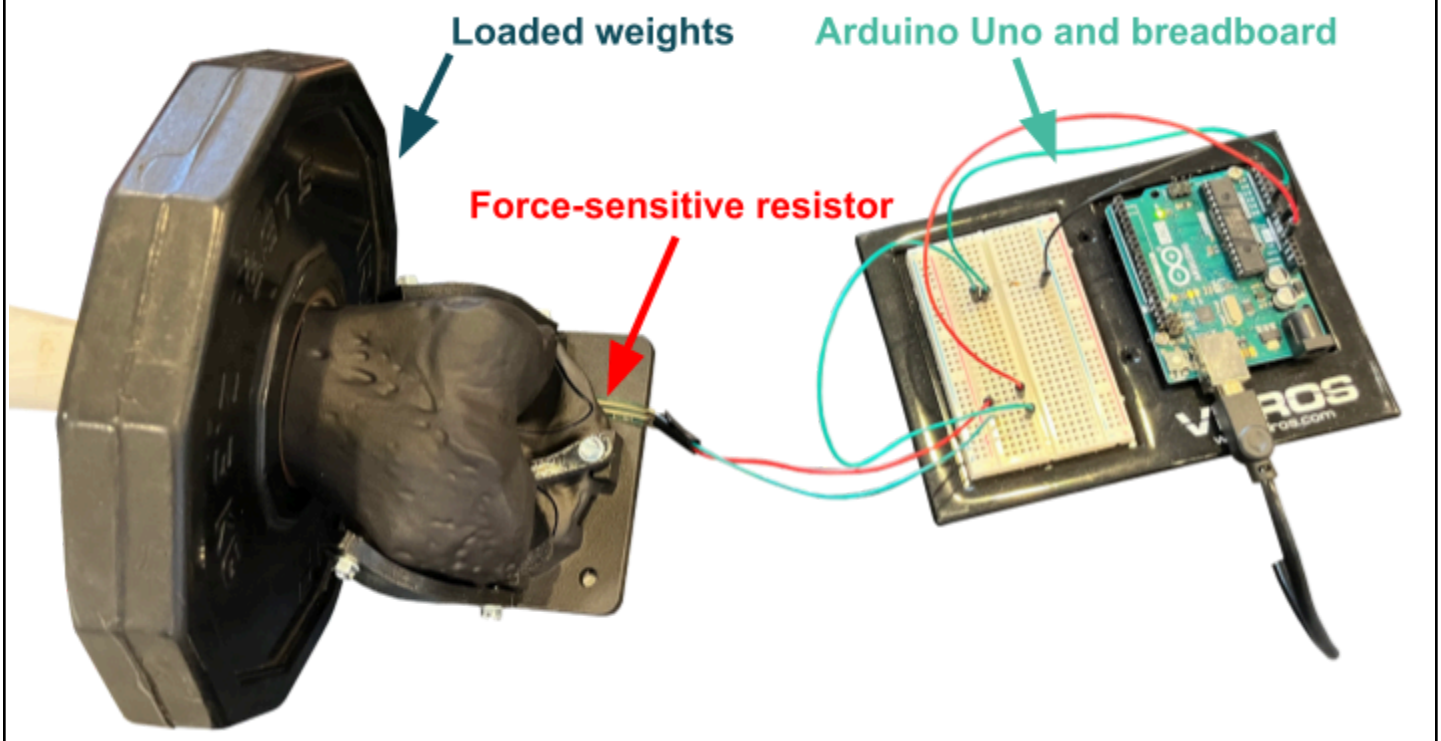

Fig. S7. Final physical model setup (Aim 2). This image shows the model at the horizontal (0°) position with 5 lbs loaded.