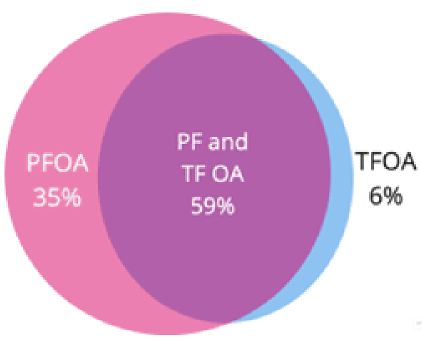
The Math Behind Patellofemoral Joint-Unloading: Force Vectors Explained

Knee osteoarthritis (OA) is a debilitating condition affecting millions worldwide. It manifests in the degradation of articular cartilage within the knee joint, leading to pain, stiffness, and impaired mobility. The knee consists of three primary compartments: the medial tibiofemoral, lateral tibiofemoral, and patellofemoral compartments. Each compartment can be impacted by OA, resulting in complex clinical presentations. Traditional unloader braces only address medial and lateral tibiofemoral OA—overlooking patellofemoral OA (PFOA) despite its high prevalence (see Figure 1). This white paper provides an in-depth analysis of the forces experienced in the patellofemoral joint (PFJ), methods used to calculate these forces, and Icarus' innovative approach to reducing them.

Figure 1: Recent studies have indicated that the majority of knee osteoarthritis cases involve the patellofemoral compartment, with 59% of patients presenting multi-compartment OA, 35% presenting isolated patellofemoral OA, and 6% presenting isolated tibiofemoral OA.



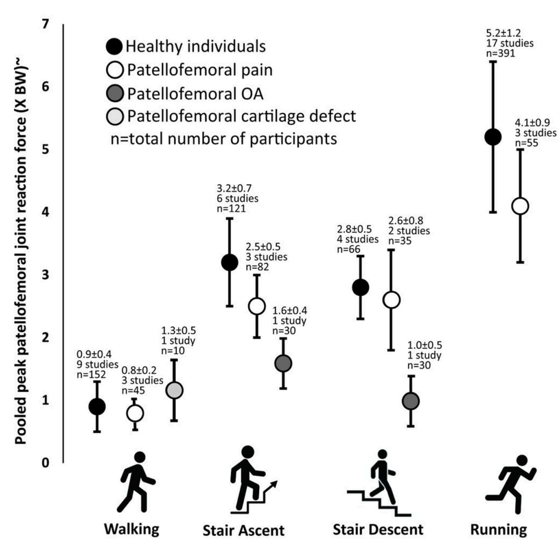
Pressure in the Patellofemoral Compartment Based on Activity

Anatomically, the knee operates as a fulcrum joint to create mechanical advantage, leading to substantial force levels within the joint, particularly in the patellofemoral compartment during activity. These forces are not merely a function of the patient's body weight, but are significantly amplified by factors such as acceleration (activity intensity) and knee flexion angle. Activities like squatting, climbing stairs, and running exponentially increase these forces relative to walking, placing substantial stress on the patellofemoral cartilage and contributing to osteoarthritis (OA) progression (Karadsheh et al., 2017) (see table 1 and figure 2). Peak force in the knee can be significantly higher than what is shown in Table 1 and Figure 2 when acceleration/deceleration are considered, and their resulting impulse forces.

Table 1: Forces generated in the patellofemoral compartment, represented as a multiple of body weight depending on the intensity of activity and flexion angle of the knee (RSNA, 2019).

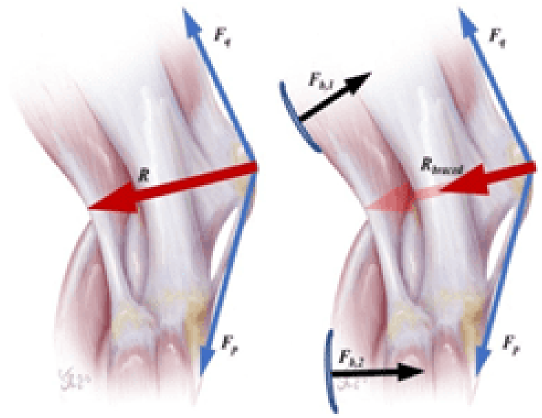
Activity	Force (lbs)	Body Weight Multiple
Walking	100	1/2 x BW
Bike	100	1/2 x BW
Stair Ascend	660	3.3 x BW
Stair Descend	1000	5 x BW
Jogging	1400	7 x BW
Squatting	1400	7 x BW
Deep Squatting	4000	20 x BW

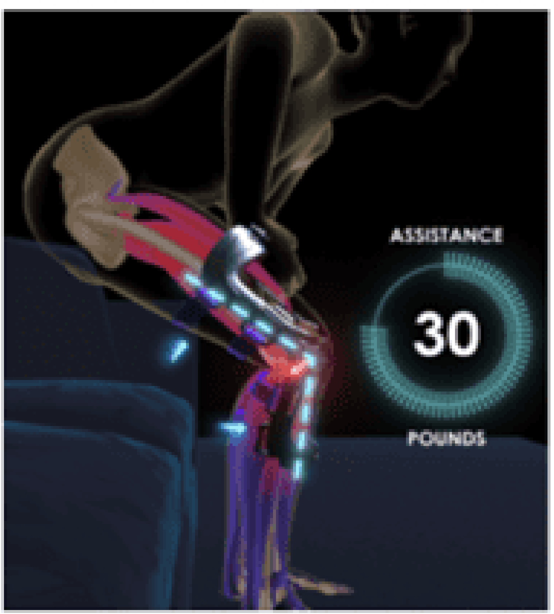
Figure 2. Peak patellofemoral joint reaction force (PFJRF) in terms of multiple of body weight (xBW) during therapeutic exercises and physical interventions, according to a review and meta-analysis of literature on the patellofemoral joint.



Fulcrum Joint Dynamics and Force Vectors: Natural and Braced

Key Components and Forces





1. **Quadriceps Force (F_q)**: Represented by the blue arrow pointing upward, this force is generated by the contraction of the quadriceps muscle. It pulls the patella upwards, exerting a force along the quadriceps tendon and a force of the same magnitude on the patella tendon (Fp).
2. **Resultant Force (R)**: Represented by the longer red arrow in the figure, this is the force experienced in the patellofemoral compartment as a result of the quadriceps force. The resultant force is directed inward toward the femur, indicating the force pressing the patella against the femoral surface.
3. **Brace Forces ($F_{b,1}$ and $F_{b,2}$)**: This is the counterforce applied by the Ascender knee brace. It is represented by the black arrows in the diagram. The brace force acts at strategic points around the knee, assisting with extension and counteracting the forces generated by the quadriceps and other structures.
4. **Resultant Force with Brace (R_{braced})**: This shorter red arrow represents the resultant force vector when the brace is applied. The force generated by the quadriceps decreases when the brace is applied, which in turn reduces the resultant force pressing the patella against the femoral surface.

Explanation:

The brace's application of force **(F_b)** opposes the natural forces exerted by the quadriceps that control flexion. By generating a counterforce, the brace helps to reduce the force in the quadriceps, and co-contracting muscles, therefore reducing the overall compressive forces within the knee joint—resulting in the reduced **R_{braced}**. This is crucial for alleviating pain and preventing further damage to the joint structures, particularly in patients with patellofemoral pain syndrome (PFPS) and osteoarthritis (OA).

The reduced resultant force implies lower stress on the joint surfaces, the patellofemoral joint in particular, contributing to decreased pain and improved function. This analysis also illustrates the unloading is not limited to the patellofemoral joint; this produces tri-compartment unloading during flexion.

Calculating Forces in the Patellofemoral Joint

The forces in the patellofemoral compartment are primarily caused by the pulling force of the quadriceps **(F_q)** and patella tendon **(F_p)** on the patella. Mathematically, these force vectors can be added together to determine the resultant force or net force driving the patella into the femur **(R)** during flexion. Analysis of the pressures in the patellofemoral compartment based on activity also highlight the positive relationship between degree of knee flexion and patellofemoral pressure (see Table 1), where activities such as deep squatting generate more than double the amount of force as shallower squats and jogging.

To calculate the patellofemoral joint force **(R)** in a static patient, we need to take into account both the pulling force generated by the quadriceps, and the knee flexion angle **(θ)**—where the greater the knee flexion angle, the greater the patellofemoral pressure.

As the knee flexes, the angle increases, causing changes in the magnitudes of the forces involved. The equation to determine the resultant force takes into account these angles and the contributions from both the quadriceps and the brace.

$$R = 2 \cdot cos(\frac{\theta}{2}) \cdot F_q$$

In this equation:

- $\mathbf{F_q}$ is the force generated by the quadriceps.
- **θ** is the angle of knee flexion.
- **R** is the resultant force driving the patella into the femur.

In this equation, as the angle of knee flexion increases, the cosine component increases accordingly—leading to a higher resultant force. This relationship highlights that deep knee bends result in greater forces acting on the patellofemoral joint, potentially exacerbating pain and joint degeneration.

$$\textit{Person weight} = 164\ lbs\ (74\ kg\ or\ 730\ N)$$

$$\textit{Moment for deep squat} = 70\ Nm$$

$$\textit{Length of moment arm}\ (d) = 4\ cm$$

$$F_T * d = 70\ Nm$$

$$F_T * 0.04\ m = 70\ Nm \qquad F_R = 2\cos\frac{\theta}{2}F_T$$

$$F_T = 1750\ N$$

$$\textit{At 115 degrees}, FR = 2800\ N$$

This is 3.8 X body weight at 115 degrees flexion

Application: Calculating the patellofemoral pressure of a 164 lb patient at 115 degrees of flexion.

Exploiting Patellofemoral Joint Math to the Benefit of Patients with PFOA

It is well known that managing PFOA begins with weight loss recommendations, as reducing body weight significantly decreases the forces exerted on the patellofemoral joint, as thoroughly explained above. If a patient's knee is subjected to 10 pounds less, this is analogous to 50 pounds relieved from the joint, in the example of the patient going down stairs. The Icarus Ascender functions based on these concepts and prove that a small amount of weight unloaded from the knee can have a significant impact in pain relief.

The unloading device by Icarus – the Ascender – helps mitigate these forces by generating counterforces $\mathbf{F_{b,1}}$ and $\mathbf{F_{b,2}}$. These forces directly assist with extension, reducing the magnitude of $\mathbf{F_q}$. In the equation, there is a directly proportional relationship between $\mathbf{F_q}$ and **R**—meaning that any reduction in the quadriceps force will decrease **R**, the resultant pressure in the patellofemoral compartment. This reduced patellofemoral force is represented by $\mathbf{R_{braced}}$ in the figure.

To summarize this as a simple chain of events, the Ascender brace (by helping with extension) **reduces the force generated by the quadriceps, which directly reduces pressure in the patellofemoral compartment.**

Conclusion:

Mechanically unloading the patellofemoral joint through bracing to manage PFOA is effective and can be useful in conjunction with other conservative treatment options. The Icarus Ascender knee brace is new technology that offers a transformative approach to managing PFOA, a condition often overlooked by traditional unloader braces that primarily address tibiofemoral compartments. By strategically applying counterforces that reduce quadriceps-induced stress on the patellofemoral joint, the Ascender diminishes the compressive forces responsible for pain and cartilage degradation. This design not only alleviates symptoms but can also help preserve joint integrity by directly targeting the unique biomechanics of the patellofemoral compartment. The Ascender stands out as a pioneering solution, effectively bridging the gap in comprehensive osteoarthritis care and significantly improving patient outcomes.

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