Optimizing In Vitro Knee Biomechanics Research: The Utility Of Functionally Derived Joint Coordinate Systems

Dr. Lukas Schneider
Department of Orthopaedic Engineering, ETH Zurich, Switzerland

Dr. Sofia Baumgartner
Institute for Biomechanics, Swiss Federal Laboratories for Materials Science and Technology (Empa), Dübendorf, Switzerland

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ABSTRACT

Accurate characterization of knee joint kinematics is paramount for understanding musculoskeletal function, evaluating injury mechanisms, and optimizing the design of orthopedic interventions such as total knee arthroplasty. In vitro knee testing, often employing robotic systems, provides a controlled environment for these investigations. However, the precise definition of a consistent and physiologically relevant joint coordinate system (JCS) remains a critical challenge. Traditional anatomically defined JCS are susceptible to significant inter- and intra-observer variability and kinematic crosstalk errors. This article elucidates the substantial benefits of utilizing functional joint coordinate systems (FJCS) in in vitro knee testing. By deriving joint axes and origins from the actual motion of the joint, FJCS offer improved reproducibility, reduced kinematic crosstalk, and a more physiologically meaningful representation of complex knee kinematics, including coupled motions like the screw-home mechanism. We conceptually outline the methodologies for implementing FJCS in robotic in vitro setups and discuss how their application yields more reliable and accurate data for biomechanical analyses, ultimately enhancing the validity and clinical relevance of research on knee function, injury, and prosthesis performance.

Keywords: Knee joint, kinematics, in vitro testing, functional joint coordinate systems, anatomical landmarks, kinematic crosstalk, biomechanics, orthopedics, robotic testing.

INTRODUCTION

The human knee joint is a complex anatomical structure, enabling sophisticated three-dimensional (3D) movements crucial for locomotion, weight-bearing, and daily activities [1, 2]. Understanding its intricate biomechanics is fundamental to diagnosing and treating a wide array of musculoskeletal conditions, ranging from ligamentous injuries, such as anterior cruciate ligament (ACL) ruptures [4, 6], to degenerative diseases like osteoarthritis [2, 22]. Precise biomechanical analysis is also indispensable for the design and evaluation of orthopedic implants, particularly total knee arthroplasty (TKA) components, aiming to restore natural knee kinematics and improve patient outcomes [3, 23, 24].

In vitro biomechanical testing, often leveraging highly sophisticated robotic systems, serves as a cornerstone for investigating knee joint behavior under controlled and reproducible conditions [5, 7]. These experimental setups allow researchers to apply specific loads and motions to cadaveric knee specimens while simultaneously measuring resulting kinematics and kinetics. This provides invaluable insights into ligament function [6, 7], cartilage mechanics [26], and the performance of surgical reconstructions or prosthetic designs [3, 5].

A critical aspect of accurately quantifying joint motion in any biomechanical study, whether in vivo or in vitro, is the definition of a consistent and physiologically relevant joint coordinate system (JCS) [8, 9, 10]. A JCS provides a standardized framework for describing the relative orientations and movements between articulating segments. Historically, knee kinematics have often been described using anatomically defined JCS, where coordinate axes are established based on palpable bony landmarks or identifiable anatomical features [11]. However, this approach inherently suffers from significant limitations. The accurate identification of anatomical landmarks can be plagued by substantial inter-observer and intra-observer variability, even for experienced clinicians and researchers [12, 13]. Moreover, anatomical axes may not perfectly align with the true functional axes of rotation of the joint, leading to "kinematic crosstalk"—the erroneous coupling of rotations around different axes due to misalignment, which can obscure true physiological motions [14, 15, 16]. Such errors can profoundly impact the interpretation of results, potentially leading to inaccurate conclusions about joint stability, implant performance, or injury mechanisms.

To address these limitations, the concept of functional joint coordinate systems (FJCS) has emerged as a superior alternative [17, 18]. Rather than relying on static anatomical landmarks, FJCS determine the axes and origins of rotation from the actual dynamic motion of the joint during specific functional tasks. This approach theoretically yields axes that more closely represent the true physiological rotations, thereby enhancing the accuracy and reproducibility of kinematic measurements. This article aims to elucidate the multifaceted benefits of employing functional joint coordinate systems in in vitro knee testing. We will discuss how FJCS can mitigate the challenges associated with anatomical landmarking, reduce kinematic crosstalk, and ultimately provide a more reliable and physiologically meaningful description of complex knee kinematics, thereby optimizing biomechanics research and its clinical applicability.

2. Literature Review

The accurate description of knee joint motion is fundamental to biomechanics research, clinical assessment, and orthopedic innovation. This section reviews the evolution of joint coordinate systems, highlighting the limitations of anatomical approaches and introducing the advantages of functional methods.

2.1 The Importance of Knee Biomechanics and In Vitro Testing

The knee is a complex synovial joint, and its intricate kinematics are critical for activities of daily living [1, 2]. Biomechanical studies are essential for understanding knee joint function in physiological conditions, characterizing how pathologies like osteoarthritis or ligament injuries affect motion, and developing effective treatment strategies [2, 4]. In vitro testing, particularly using robotic systems, has become a powerful tool in this endeavor [5, 7]. These controlled experimental environments allow researchers to simulate various physiological loading conditions, such as those that generate high ACL forces [6], and precisely measure the resulting motion and forces. This is crucial for evaluating reconstructive techniques [7] and optimizing knee implant designs [3]. The International Organization for Standardization (ISO) even provides specific guidelines for loading and displacement parameters for wear-testing machines with knee joint prostheses, underscoring the importance of standardized in vitro evaluation [19].

2.2 Traditional Joint Coordinate Systems: Anatomical Definition and Their Limitations

A standardized framework for describing joint motion is essential for comparing results across studies [9, 10]. The Joint Coordinate System (JCS), introduced by Grood and Suntay [8] and later adopted with recommendations by the International Society of Biomechanics (ISB) [9, 10], provides a widely accepted method for defining 3D joint rotations and translations. This system typically defines a flexion-extension axis, an ab/adduction axis (varus-valgus for the knee), and an internal-external rotation axis, along with corresponding translation axes.

Historically, these JCS have often been defined using readily identifiable anatomical landmarks [11]. For the knee, this might involve defining axes based on epicondyles, tibial plateaus, or other bony features. However, relying solely on anatomical landmarks presents significant challenges:

- Inter- and Intra-Observer Variability: The palpation and identification of anatomical landmarks are inherently subjective and prone to variability, even among experienced operators [12, 13]. This variability can lead to inconsistent coordinate system definitions across different experiments or even within the same experiment conducted by different individuals, compromising reproducibility.
- Non-physiological Axis Alignment: Anatomical axes may not precisely coincide with the true axes of joint rotation, especially for complex joints like the knee, which exhibit coupled motions and instantaneous centers of rotation that shift throughout the range of motion [14]. For instance, the transepicondylar axis is often approximated as the flexion axis, but its exact relationship to the true functional axis can vary [20].
- Kinematic Crosstalk Errors: A major issue with anatomically defined JCS is "kinematic crosstalk," where a true rotation around one axis is erroneously expressed as a rotation around another, mathematically coupled axis [14, 15]. For example, if the flexion-extension axis is not perfectly perpendicular to the ab/adduction axis, a pure flexion motion might appear to include some varus-valgus rotation [16]. This artifact can obscure true physiological motions and lead to misinterpretation of joint mechanics [14, 16]. Research has shown that knee kinematic descriptions are highly sensitive to errors in axis alignment [14].

These limitations underscore the need for more robust and accurate methods for defining JCS, particularly in the context of high-precision in vitro biomechanical testing.

2.3 Functional Joint Coordinate Systems: A Superior Approach

To overcome the inherent limitations of anatomical landmarking, "functional joint coordinate systems" (FJCS) have been developed and increasingly adopted [17, 18]. Unlike anatomical methods, FJCS derive joint axes and origins from the actual dynamic motion of the joint during specific, repeatable tasks. This approach assumes that the repeated motion reflects the underlying anatomical and functional constraints of the joint.

Key characteristics and advantages of FJCS include:

- Reduced Variability: By deriving axes from motion, FJCS are less susceptible to the subjective variability associated with anatomical landmark palpation [12, 13]. This leads to more reproducible JCS definitions.

- Physiological Relevance: Functional axes often align more closely with the true, instantaneous axes of rotation of the joint, capturing the natural biomechanics more accurately [17, 18]. This is particularly important for complex, multi-axis movements like knee flexion-extension, which includes the "screw-home mechanism" [14, 27, 28, 29, 30, 31]—a coupled internal rotation of the tibia relative to the femur during terminal knee extension. Anatomical methods often struggle to capture this coupled motion accurately without significant crosstalk [14, 16].

- Minimizing Kinematic Crosstalk: By explicitly defining axes based on observed motion, FJCS can significantly reduce or eliminate kinematic crosstalk errors [16, 17]. This provides a cleaner, more accurate representation of individual degrees of freedom (e.g., pure flexion-extension, pure varus-valgus rotation), which is critical for precise biomechanical analysis.

- Improved Accuracy in Kinematic Description: Studies have shown that FJCS can achieve clinically meaningful kinematics of the tibiofemoral joint compared to ISB recommendations, particularly in minimizing crosstalk [17]. A generalized framework for determining functional musculoskeletal JCS has been proposed, further standardizing this approach [18].

- Relevance to Specific Knee Kinematics: FJCS are particularly beneficial for accurately characterizing subtle yet clinically important knee kinematics. This includes quantifying varus-valgus laxity, which is crucial for assessing knee stability in conditions like osteoarthritis [22, 23] and for evaluating implant performance [23]. Accurately capturing the screw-home mechanism is also vital for understanding normal knee function and evaluating the effectiveness of TKA designs [27, 29, 30]. Healthy knee kinematic phenotypes have even been identified using clustering data analysis, which relies on accurate kinematic description [25].

In summary, the transition from purely anatomical to functionally derived JCS represents a significant advancement in biomechanical methodology, offering a more robust and accurate foundation for in vitro knee testing.

3. Methods (Conceptual Application of FJCS in In Vitro Testing)

This section conceptually outlines the methodology for implementing and leveraging functional joint coordinate systems (FJCS) within an in vitro robotic knee testing environment. As this is a conceptual article focusing on benefits, the "methods" describe the envisioned process of applying FJCS rather than presenting specific empirical steps of a novel experiment.

3.1 Robotic In Vitro Knee Testing Setup

The described methodology would be applied within a high-precision robotic testing system, such as a six-degree-of-freedom (6-DOF) robotic arm [5, 7, 33].

- Specimen Preparation: Cadaveric knee specimens (femur, tibia, and associated ligaments/capsule) would be meticulously prepared, ensuring intact soft tissues and removal of surrounding musculature. The femur and tibia would be rigidly potted in polymethyl methacrylate (PMMA) cups to secure them to the robotic system's fixtures.

- Robotic System Integration: The potted femur and tibia would be mounted to the robotic arm, with either the femur or tibia fixed, and the other segment connected to the robot's end-effector. The robotic system allows for precise application of forces and moments, as well as measurement of resulting joint motions (kinematics) [5]. A generalized framework might be used for determining functional musculoskeletal joint coordinate systems [18].

- Load and Motion Application: The robotic system can apply various loading conditions (e.g., anterior-posterior tibial translation, varus-valgus rotation, internal-external rotation) and impose specific motion pathways (e.g., knee flexion-extension cycles) [5, 6]. ISB recommendations on reporting intersegmental forces and moments would be followed [32].

3.2 Determination of Functional Joint Coordinate Systems

The core of this methodology lies in the determination of FJCS from the inherent motion of the knee joint. This process typically involves specific functional maneuvers performed by the robotic system.

3.2.1 Flexion-Extension Axis Determination (e.g., Helical Axis Method)

- The robotic arm would impose a large range of passive flexion-extension motion on the knee specimen (e.g., from full extension to 120 degrees of flexion).

- During this motion, the 3D position and orientation of the tibia relative to the femur would be continuously tracked.

- The helical axis (or finite helical axis) method would be applied to the collected kinematic data. This mathematical technique identifies the instantaneous axis of rotation for a given motion [18]. By averaging or optimizing these instantaneous axes over a significant range of motion, a single, functionally derived flexion-extension axis can be determined. This functionally derived axis represents the most stable and repeatable axis of rotation for flexion-extension.

3.2.2 Varus-Valgus and Internal-External Rotation Axes

- Once the functional flexion-extension axis is established, it can serve as a reference.

- Varus-Valgus (VV) Axis: This axis is typically defined as being perpendicular to the flexion-extension axis and lying in the sagittal plane of the femur or tibia. Functionally, it can be derived by applying controlled varus-valgus moments and observing the resulting rotations or by defining it relative to the functionally determined flexion axis.

- Internal-External (IE) Rotation Axis: This axis is defined as perpendicular to both the flexion-extension and varus-valgus axes, completing an orthogonal set. It is usually aligned with the longitudinal axis of the tibia or femur, passing through the functional center of rotation.

3.2.3 Origin of the Joint Coordinate System

The origin of the FJCS is typically located at the intersection of the defined functional axes, or at a functionally determined center of rotation.

3.3 Application of FJCS in Kinematic Measurements

Once the FJCS are established for a given knee specimen, all subsequent kinematic measurements would be reported relative to this functionally defined system.

- Data Collection: Motion capture systems (e.g., optical tracking markers, internal encoders of the robot) would record the 3D positions and orientations of the femoral and tibial segments throughout various loading and motion protocols [5].

- Kinematic Calculations: Transformation matrices would be used to convert the raw motion data into rotations and translations about the functionally derived axes. This process would inherently minimize kinematic crosstalk, as the axes are optimized for the joint's natural motion [17].

- Specific Kinematic Assessments:

o Screw-Home Mechanism: The coupled internal-external rotation of the tibia during terminal knee extension would be accurately quantified, as FJCS are specifically designed to capture such coupled motions without artificial crosstalk [17, 28, 29, 30].

o Varus-Valgus Laxity: The rotational stiffness and angular displacement of the knee under varus-valgus moments would be precisely measured, providing a clearer indication of ligamentous stability [22, 23].

o Anterior-Posterior Tibial Translation: The amount of translational laxity in the sagittal plane would be accurately determined, crucial for evaluating ACL and PCL integrity [6].

3.4 Data Analysis and Reporting

Kinematic data, expressed within the FJCS, would undergo statistical analysis to compare different conditions (e.g., intact vs. injured vs. reconstructed knees). Reporting of data would adhere to ISB recommendations for intersegmental forces and moments [32], ensuring clarity and comparability with other studies. The benefits of FJCS would be quantified by comparing results obtained using FJCS to those obtained using traditional anatomical JCS on the same specimens, highlighting the reduction in crosstalk and improved physiological representation.

4. Results (Hypothetical Illustrations of Benefits)

This section presents hypothetical results, derived from the conceptual application of functional joint coordinate systems (FJCS) in in vitro knee testing, illustrating the expected and documented benefits of this methodology in providing more accurate and physiologically meaningful kinematic data.

4.1 Significant Reduction in Kinematic Crosstalk Errors

Hypothetical results would demonstrate a statistically significant reduction in kinematic crosstalk when using FJCS compared to conventional anatomically defined joint coordinate systems.

- Flexion-Extension Dominance: When a pure flexion-extension motion is imposed on the knee specimen, kinematic data reported using an anatomically defined JCS might show spurious "crosstalk" rotations around the varus-valgus and internal-external axes (e.g., 5-10 degrees of unintended coupled motion). In contrast, data reported using a functionally derived JCS would show negligible or near-zero rotations around these orthogonal axes, indicating that the flexion-extension motion is accurately isolated [16, 17].

- Improved Orthogonality: The calculated orthogonality of the functional axes (flexion-extension, varus-valgus, internal-external) would be significantly closer to 90 degrees, demonstrating a geometrically superior coordinate system that minimizes mathematical coupling errors.

4.2 Enhanced Reproducibility and Reduced Variability

The use of FJCS would lead to improved reproducibility of knee kinematic measurements across multiple trials and specimens.

- Lower Intra-Trial Variability: For repeated flexion-extension cycles on the same specimen, the standard deviation of kinematic parameters (e.g., screw-home rotation, varus-valgus angle at specific flexion angles) would be lower when measured using FJCS compared to anatomical JCS. This highlights the inherent stability of axes derived from motion.

- Reduced Inter-Specimen Variability: While biological variability between specimens cannot be eliminated, the functional definition of axes would reduce the component of variability attributable to imprecise landmarking. This would allow for clearer identification of true biological differences in kinematic behavior.

4.3 More Physiologically Meaningful Kinematics

FJCS would enable a more accurate and physiologically meaningful description of complex knee motions.

- Accurate Screw-Home Mechanism

Characterization: The typical external rotation of the tibia relative to the femur during terminal extension (the screw-home mechanism) [28, 29, 31] would be distinctly and consistently observed and quantified with greater precision using FJCS (Figure 1a). Anatomical systems often struggle to separate this coupled rotation from pure flexion-extension, leading to less reliable measurements [14].

- Clearer Varus-Valgus Laxity Profiles: The measurement of varus-valgus angles under applied moments would yield cleaner and more reliable laxity curves. This would allow for a more precise assessment of ligamentous contributions to knee stability, crucial for evaluating injury or surgical repair [22, 23]. For example, the laxity values at specific flexion angles (e.g., 0°, 30°, 90°) would be more consistent and reflective of the knee's true stability (Figure 1b).

- Precise Tibiofemoral Translations: Translational kinematics, such as anterior-posterior tibial translation, would be more accurately measured relative to the functionally derived origin, providing a more robust assessment of joint translation under various loading conditions [6].

4.4 Improved Sensitivity for Assessing Surgical Interventions and Prosthesis Performance

The enhanced accuracy afforded by FJCS would provide greater sensitivity for detecting subtle biomechanical changes due to surgical interventions or prosthetic implantation.

- ACL Reconstruction Evaluation: In studies evaluating ACL reconstruction techniques, FJCS would enable more precise quantification of restored anterior-posterior and rotational stability (e.g., internal-external rotation during dynamic tasks) compared to the native knee [7]. This increased precision is vital for determining the efficacy of different graft choices or tunnel placements.

- Total Knee Arthroplasty (TKA) Kinematics: When evaluating TKA designs, FJCS would allow for a more detailed characterization of condylar lift-off, screw-home motion, and overall kinematic patterns (e.g., rolling and gliding motions) of the prosthetic components [27, 30]. This would help in assessing how well the implant replicates natural knee kinematics and identifying deviations that could impact long-term performance or patient satisfaction. This enhanced sensitivity is crucial for evaluating prosthetic design parameters, such as the sagittal curvature of femoral condyles [21], and their influence on joint motion.

5. Discussion

The hypothetical results emphatically underscore the significant advantages of integrating functional joint coordinate systems (FJCS) into in vitro knee biomechanics testing. By addressing the inherent limitations of traditional anatomical landmarking, FJCS offer a pathway to generate more accurate, reproducible, and physiologically meaningful kinematic data, which is paramount for advancing orthopedic research and clinical practice.

The most compelling benefit is the substantial reduction in kinematic crosstalk. The knee joint exhibits complex coupled motions, such as the screw-home mechanism [14, 28, 29, 31], where rotation around one axis is naturally accompanied by rotation around another. Anatomical JCS, if not perfectly aligned with these true functional axes, often artificially couple motions, leading to a misrepresentation of the actual kinematics [14, 16]. By deriving axes from the joint's actual motion, FJCS are optimized to minimize these mathematical artifacts, providing a cleaner, more accurate description of individual degrees of freedom. This clarity is not merely an academic refinement; it directly impacts the interpretation of data, allowing researchers to discern true biological and mechanical phenomena from measurement artifacts.

The enhanced reproducibility and reduced variability afforded by FJCS are also critical for robust research. The subjective nature of anatomical landmark palpation introduces inherent errors that can obscure real differences between experimental conditions or specimens [12, 13]. FJCS, being derived from repeatable motions, intrinsically mitigate this source of variability, leading to more consistent JCS definitions. This increased precision translates to greater statistical power in studies, allowing researchers to detect smaller, yet clinically relevant, biomechanical changes, ultimately making research findings more reliable and generalizable.

The ability of FJCS to capture more physiologically meaningful kinematics is particularly relevant for understanding complex knee function and evaluating orthopedic interventions. Accurate characterization of coupled motions like the screw-home mechanism, along with precise quantification of varus-valgus laxity [22, 23], is essential for developing implants that truly replicate natural knee function and for evaluating surgical techniques that restore physiological stability [7]. For instance, the fidelity with which a total knee arthroplasty replicates normal screw-home motion can significantly impact patient satisfaction and functional outcomes [27, 30]. By providing a more accurate kinematic fingerprint of the knee, FJCS can directly inform implant design modifications and personalized surgical planning. This also extends to understanding healthy knee kinematic phenotypes, which can be better identified with accurate kinematic data [25].

5.1 Implications for Orthopedic Research and Clinical Practice

The adoption of FJCS in in vitro knee testing has broad implications:

- Improved Implant Design: More accurate kinematic data from FJCS can lead to the design of knee prostheses that better mimic natural joint motion, potentially reducing wear, improving stability, and enhancing patient function [3, 21].

- Enhanced Surgical Planning: By precisely quantifying the biomechanical effects of various surgical techniques (e.g., ACL reconstruction, ligament balancing in TKA), FJCS can help optimize surgical protocols and improve patient outcomes [7].

- Foundation for Computational Models: Accurate in vitro data generated using FJCS can serve as critical validation data for computational models (e.g., finite element models of the knee joint [26]), improving their predictive capabilities and clinical relevance.

- Standardization: The development of generalized frameworks for FJCS [18] can contribute to greater standardization in biomechanical testing, facilitating better comparison of results across different laboratories worldwide, similar to ISB recommendations [9, 10, 32].

5.2 Limitations and Future Directions

While FJCS offer substantial benefits, their implementation also presents certain considerations and avenues for future research:

- Complexity of Determination: Deriving FJCS can be more computationally intensive and technically complex than simple anatomical landmarking. However, advancements in robotic control systems and processing power, including hybrid control systems [33], are making this increasingly feasible.

- Dependence on Functional Motion: The accuracy of an FJCS relies on the chosen functional motion accurately reflecting the true physiological behavior of the joint. Different functional maneuvers might yield slightly different axes, necessitating standardization of these calibration motions.

- In Vivo Translation: While highly beneficial for in vitro studies, the direct translation of FJCS determination to in vivo settings can be challenging due to limitations in motion capture and soft tissue artifact. Further research is needed to develop robust in vivo FJCS methods.

- Standardization and Reporting: While frameworks exist [18], wider adoption requires clear guidelines and consensus on specific functional motions and algorithms for FJCS determination to ensure true comparability across studies.

Despite these considerations, the advantages of using FJCS in in vitro knee testing are compelling. Their ability to provide more accurate, reproducible, and physiologically relevant kinematic data makes them an indispensable tool for advancing our understanding of knee biomechanics.

CONCLUSION

The pursuit of accurate knee joint kinematic characterization is fundamental to orthopedic biomechanics. This article has underscored the profound benefits of moving beyond traditional anatomical landmarking to embrace functionally derived joint coordinate systems (FJCS) in in vitro testing. By mitigating the issues of inter-observer variability and, crucially, eliminating kinematic crosstalk, FJCS enable a more precise and physiologically meaningful description of complex knee motions, including vital coupled movements like the screw-home mechanism. The enhanced reproducibility and accuracy afforded by FJCS directly translate into more reliable data for evaluating injury mechanisms, optimizing surgical techniques, and refining orthopedic implant designs. As in vitro robotic testing systems continue to evolve in sophistication, the integration of FJCS stands as a critical methodological advancement, ensuring that biomechanical research generates insights that are not only scientifically rigorous but also directly applicable to improving clinical outcomes for patients with knee disorders.

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