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Design of a Unified Compact Rig for Knee Slider and Impact Testing

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Abstract

The calibration of anthropomorphic test device knee assemblies is a critical requirement in vehicle safety assessment to ensure reliable biomechanical response under impact and sliding load conditions. Knee impact and slider calibration rigs conventionally available are typically large, single functional systems and also demand large laboratory space and reconfiguration, limiting their application in many research and testing environments. This paper presents the design and further analytical validation of a compact and integrated test rig which combines the function of both knee impact and slider tests. The proposed design is based on pendulum dynamics to achieve kinematic conditions under compliance of standards. Analytical calculations and design verify that the rig can be configured to achieve required impact and slider velocities adhering to relevant automotive calibration standards by appropriate selection of impactor mass, pendulum geometry, and actuation parameters. System footprint is reduced owing to compact design while maintaining structural stiffness, alignment integrity, and repeatability by design. Rig presented here offers a practical, compact design framework for knee calibration while following the standards and establishes a foundation for future prototype development and experimental validation.

Keywords: Anthropomorphic Test Device; Knee Impact Calibration; Knee Slider Test; Compact Calibration Test Rig; Dual-Mode Test Rig

How to Cite This Article

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Introduction

Background and Motivation

Assessment accuracy of occupant safety in frontal vehicle collisions mainly depends on the use of anthropomorphic test devices (ATDs) whose biomechanical responses closely replicate those of humans. Knee joint is complex biomechanical structure and highly prone to injury during human impacts of human and vehicle and hence it is the area of interest. Calibration procedures for dummy knees such as knee impact tests and slider tests are important as to ensure that the knee assembly responds correctly under defined loadings and deflections.[1,2]

These calibration tests are widely conducted using separate, dedicated test rigs: one for the knee impact event in which an impactor mass strikes the knee assembly at controlled speed/energy and another for the knee slider event where a shear/sliding motion is applied to the tibia-knee assembly.[3] These setups are usually bulky, and require large laboratory space, complex alignment procedures, and timely reconfiguration. Such large test frames create limitations in many research laboratory settings such as high space consumption, difficulty in alignment and mode interchange, increased cost and maintenance, and constraints on positioning or installation in small spaces.

Recent research trends show increase in interest of compact, modular, and integrated test equipment that combine functions while reducing footprint and improving repeatability. For example, an inexpensive, additively manufactured knee test rig has demonstrated that even complex knee mechanisms can be evaluated in a smaller rig environment.[4] Inspite of developments, there remains a lack of a single, compact test rig solution which integrates both knee impact and slider calibrations while maintaining repeatability and compliance with ATD calibration standards.

Hence, the present work is derived by the need to develop an innovative, efficient in space consumption, highly repeatable test rig being capable of performing both knee impact and slider calibration tests in a single system. The described design aims to maintain compliance with established calibration standards (e.g., AIS-098) while being reusable, and adapting to laboratory environments, and improved operational efficiency.[5,6]

Research Gap and Proposed Design

Although calibration test rigs for dummy knees specifically for knee impact and slider evaluations have been developed since long times, but there exists several limitations in currently available systems that hamper their efficiency, integration, and application in small laboratory environments. Below are the key gaps identified:

Bulky and separate test setups: Most existing calibration systems treat knee impact and slider tests as two different procedures, and also require separate fixtures, actuators, and alignment frames. For example, a commercial rig measures a boundary of approximately 4.9 m × 1.2 m × 2.9 m for a dual function knee impact and slider test frame.[7] These large dimensions result in vast area consumption, difficulty in alignment and mode interchange, increased cost and maintenance, and the installation and portation is also huge challenge.

Limited integration of multiple test modes: Industrial standard procedures such as SAE J2876 govern low speed knee slider test protocols for ATDs,[8] and there are lack of rigs that combine both knee impact and knee slider testing in a single, reconfigurable platform. In existing research, compact rigs are often designed for orthopedic joint simulations and not specifically for ATD calibration of dummy knees.[4] Hence, calibration systems for ATD knee assemblies still rely on separate dedicated assemblies, making automation, standardization, and data consistency across modes more problematic.

Insufficient repeatability and re-configuration time: Multiple alignment, interchanging fixtures, actuator switchover, and instrumentation routing introduce sources of error, and tests become less repeatable. For example, robotic joint test platforms developed for prosthetic knee performance assessment indicate the need for precise calibration and modular rig design to ensure reliable and repeatable results.[9] Also, the lack of integrated mechanisms directs increased downtime between test modes, which is not efficient for frequent calibration works.

Space, cost and access limitations to laboratory: Research labs mainly those in universities or smaller institutions often lack the space or budget for large single mode calibration rigs. Hence, there is an increase in demand of a compact and integrated test rig that combines both test modes and ensure increase in repeat cycles.[4,10] But, such rigs typically focus on kinematic or clinical knee research rather than dummy calibration rigs per se.

Lack of standard complying dual mode calibration rigs: Though there are modifications and novel rig designs in fields related, but there is no documented system that mainly combines the knee impact and slider calibration tests according to ATD-calibration standards (such as AIS-098) in a single rig.[5,6] This gap hinders full workflow efficiency and consistent calibration under a unified system.

How the Proposed Design Addresses These Gaps: In view of the aforementioned research gaps, this paper proposes the design of a compact, integrated calibration test rig for dummy knee evaluation, combining both the knee impact and slider test modes in one frame. Key features included in the design are given below,

- Unified frame architecture enabling switching between modes without fully disassembling, hence reducing alignment and setup time.
- Reduced size design, targeting realistic laboratory dimensions while maintaining structural stiffness and dynamic performance compared to larger rigs.[11,12]
- Shared instrumentation and sled/guide assembly, so that sensors, DAQ, and sled mechanics are common between modes making process easy to repeat and reduce lengthy setup.[13,14]
- Quick change actuator modules: one for impact and one for slider, mounted to a common sled rail.[2,33]
- Compliance with calibration standards: The rig is designed to meet the probe mass, velocity, alignment, and instrumentation requirements as given in standards such as AIS-098 and SAE J2876.[5,8,15]
- Modularity and accessibility: Components are selected in such way as to be assembled using largely available actuators, precision rail guidance, and a rigid base frame, enabling replication in standard laboratory environments.[18,19]

By addressing the above gaps, the proposed rig aims to enable more efficient, repeatable, and space efficient calibration of dummy knees for impact and slider tests, and thus contributing to improved ATD calibration workflows, making research accessible to all, and easy setup in safety testing laboratories.

Problem Statement

Existing conventional dummy knee calibration systems are physically divided into two different setups one for the knee impact test and another for the knee slider test. These conventional rigs are very big, require independent fixtures and actuators, and large number of alignment between tests. Hence there is large space requirements, low operational efficiency, and limited repeatition across calibration modes.[7,25]

There is currently no test rig which complies to standards and is capable of performing both knee impact and knee slider calibrations both in a single rig setup.[2,33] This lack of integration leads to redundancy, increased testing time, and reduced consistency in dummy knee evaluation outcomes.

Hence, there is a clear need for the design of a compact, integrated calibration test rig which combines both test modes while maintaining compliance with established standards such as AIS-098 and SAE J2876, which also ensures repeatability, reduces area required, and laboratory adaptation.[5,8,16]

Research Objectives

The primary objective of this research is to design a compact, integrated test rig that is capable of performing both knee impact and slider calibration tests for dummy knee assemblies in accordance with AIS-098 and SAE J2876 standards.[5,8]

To achieve this, the study focuses on the following specific objectives:

- Analyze existing knee calibration test rigs and identify their structural, spatial, and functional limitations.
- Develop a unified design framework which integrates both knee impact and slider tests in a single rig.
- To optimize the rig structure and make it compact, modular, and ease configuration between test modes.
- To ensure that the design is repeatable and reproducible of test results under controlled impact and slider conditions.
- To validate that the proposed design is complying with AIS-098 and related calibration requirements.
- To propose a rig architecture which can be fabricated and assembled in standard laboratory environments without costly infrastructure or instrumentation and within availabe space.

Novelty and Contributions of the Present Study

Novelty of this work lies in the design of a compact, integrated calibration test rig for anthropomorphic test device (ATD) knee assemblies which integrates knee impact and slider calibration in a single framework. Unlike conventional calibration systems that requires large, single function rigs, the proposed design undertakes a space efficient architecture while also maintaining analytical compliance with established calibration standards.

The key contributions of this study are summarized as follows:

1. A compact, dual mode calibration rig which is capable of supporting both knee impact and slider calibration configurations within a single frame.
2. An analytically verified design methodology based on pendulum dynamics and kinematic constraints to achieve AIS-098 and SAE J2876 standard velocity without relying on large structural frames.

3. A unified guide and mounting system which minimizes the alignment variation between calibration modes, and thereby enhancing repeatability by design and reducing reconfiguration effort.
4. A laboratory friendly rig concept that significantly reduces footprint and further simplyfying, which enables deployment in academic and smaller research laboratories where conventional calibration rigs are not feasible.
5. A scalable and modular design framework that establishes a foundation for future prototype development, experimental validation, and extension to other lower limb calibration applications.

The remainder of this paper is organized as follows. The literature for knee impact and slider calibration systems, applicable standards, and compact test rig designs is reviewed in Section 1.6. Section 2 describes the methodology used, including design constraints, unified rig architecture, and analytical formulation to achieve impact and slider standard velocities. The analytical results and their implications are discussed in Section 3. Finally, Section 4 concludes the paper with key findings and gives direction for future work.

Literature Review

A set of national and international standards control the calibration of anthropomorphic test device (knee assemblies) and they define fixture geometry, impactor mass and velocity, instrumentation requirements, environmental conditioning, and acceptance conditions for biomechanical response. In India, AIS-098 (Automotive Industry Standard) provides the procedural and hardware requirements for dummy knee impact testing including the required components of the knee assembly, specified impactor masses, and the fixture arrangement procedure used for knee impact certification.[5,6]

Various national and international procedures also govern related aspects of lower limb testing and data acquisition. SAE J2876 defines the recommended practice for low speed knee slider certification tests for Hybrid-III ATDs and is higky followed where knee slider certification is required; it prescribes test speeds, slider geometry, and acceptance value range requird to reproduce low energy impact behavior in certification contexts.[8]

Accurate transducer selection, channel conditioning, and data handling protocols are important factors to ensure meaningful comparison across different laboratories. SAE J211 which looks after Instrumentation for Impact Tests is the widely adopted practice specifying channel types, filtering procedures, and calibration steps for impact test instrumentation and adhering to J211 recommendations implies the comparable and repeatable nature of impact test signals used in knee calibration work.[15]

ISO/IEC 17025 further controlls the laboratory competence and calibration tracing, which creates requirements for testing and calibration laboratories which includes task such as management, technical competence, measurement uncertainty, and traceability. A calibration rig intended for use by research laboratories or certification bodies that are compliant with ISO/IEC 17025 or operating under an ISO/IEC 17025 accredited laboratory is a centre to ensure that measured knee response parameters are technically defensible and reproducible across installations.[16]

US regulatory and certification documents also provide additional procedures for knee assemblies and test conditioning. For example, the US ATD knee test procedure within the Code of Federal Regulations (49 CFR 572.176) specifies conditioning, mounting, and execution details of test for knee assemblies used in Federal Motor Vehicle Safety Standards (FMVSS) contexts; such regulatory prescriptions imply handling of specimen and conditioning protocols used widely across certification laboratories.[17]

Apart from the standards, guidance and laboratory manuals from national testing agencies for example, ARAI's laboratory operational and test method documents also further provide insights such as fixture drawings, environmental conditioning, certification frequencies, and these practical documents are used frequently by labs to design or validate their calibration rigs.[18,19]

The combination of these standards shows three points directly monitoring the rig design process: (1) calibration tests require precise energetic control including impactor mass, velocity, slider speed/stroke ; (2) consistent instrumentation and signal processing are important for comparing inter lab; and (3) fixture geometry, specimen mount, and environmental condition must be repeatable and traceable to standard criteria. As these requirements need to be strictl followed, most certified rigs in industry and accredited labs are built by purpose and are relatively large in size, with dedicated fixtures for each calibration mode which explains the fragmentation of knee impact and slider tests into separate systems in practice.[5,8,15,16]

Recent developments in protocol such as updates to national AIS documents and Euro NCAP protocol evolutions and research grade rigs show an increasing trend toward more modular and compact equipment, but also dual function rigs that remain fully compliant with standard acceptance range have not been widely addressed in the open literature. This gap creates an opportunity to design an integrated rig which satisfies the impact energy and instrumentation constraints of existing standards while simultaneously reducing laboratory space requirement and changeover time.[6,20,21,22]

The literature on anthropomorphic test device (ATD) calibration test setups for lower limb impact assessment shows a clear transition from bulky frames toward compact, modular, and automated setups while following the necessary. Fundamental calibration requirements are established by standards such as AIS-098, SAE J2876, SAE J211, and ISO/IEC 17025.[5,8,15,16] These standards give the essential parameters which are the impactor mass and velocity, boundary conditions, filtering class, and instrumentation required which control the fidelity of dummy knee testing. However, their stringent process setups often restrict the use of heavy, single functional rigs that occupy large laboratory space for different calibration modes.

Recent investigations (2020–2025) highlight this gap by proposing innovative mechanical and instrumentation strategies that maintain compliance while also reducing the overall size and mechanism.[4,11,29,30] These studies demonstrate that precise velocity control, repeatable force, and biomechanical standards are achievable using compact structures when stiffness, damping, and alignment are optimized.

Further studies stress on computational design integration, including finite element based structural optimization and parametric design approaches with help of simulation, which enable improved stiffness, linear response, and accelerated design iteration without increasing system mass.[23,24] Integrated architectures combining knee impact and slider mechanisms within a single setup have also been proposed, which highlights feasibility while at the same time identifying challenges related to mechanical reconfiguration and data acquisition switching.[2] Experimental refinement and uncertainty analysis of rig complying to AIS-098 provide benchmark validation for compact designs.[1]

Automation and closed loop control systems have been incorporated into calibration rigs to improve repetition and reduce operator influence, which is important under ISO/IEC 17025 laboratory conditions.[13,14] Comparing evaluations of knee impact rigs across multiple velocity corridors further shows the importance of high bandwidth sensors and rigid structural frames to maintain linear and repeatable operations.[25] Again additional investigations into compact biomechanical test platforms, joint motion rigs, dual stage knee simulators, stiffness dependent energy transfer, and pendulum based impact systems provide supporting insights for modern compact rig design.[3,9,10,26,27,28]

These findings studied together reveal a steady trend toward miniaturization, modularity, and automation in ATD calibration rig design. Key insights convered in several principles are: (i) use of precision linear guides or sled modules which can accommodate both impact as well as slider motions; (ii) integration of modular actuators allowing tests controlled by velocity and displacement in single frame; (iii) structural optimization for stiffness and dynamic isolation to avoid parasitic vibrations; (iv) application of high bandwidth sensors and DAQ systems consistent with SAE J211 filter classes; and (v) rapid change fixtures to make configuration time shorter between calibration modes. The reviewed literature still lacks a test rig that integrates both knee impact and slider calibration function in a single, compact, and laboratory friendly platform.

In summary, current literature establishes both the feasibility and the technological direction for integrated knee calibration systems. The combination of adherence to standards, compact mechanical design, and automated control is the main challenge and the center of motivation of the present study, which motivates to design a unified, compact rig capable of executing both AIS-098 knee impact and slider tests in a single test setup.

Experimental/Methodology

The methodology uesd in this present work is a design oriented methhod and analytical calculations to design a compact, integrated calibration test rig functional to perform both knee impact and knee slider calibration for anthropomorphic test device (ATD) knee assemblies. The scope of the present study is limited to conceptual design, constraint definition, and analytical verification. The analytical formulation, geometric configuration, and kinematic consistency with applicable standards ensure adherence to the local as well as global standards.

The overall methodology comprise of four stages:

1. Definition of space, mechanical, and standard constraints;
2. Development of a unified dual function rig architecture within these constraints;
3. Analytical determination of pendulum release angles required to achieve the standard velocities; and
4. Assessment of theoretical compliance and design repeatition.

Design Constraints and Boundary Conditions

Spatial and Laboratory Constraints: The proposed calibration rig is mainly meant for deployment in typical academic and research laboratory environments, where space availability and ceiling height is small and create problem for test infrastructure. Accordingly, the design process was started by defining explicit spatial boundary conditions to lock the overall geometry of the rig.

Here, in this study, the maximum allowable rig height was kept to 2260 mm, based on the available laboratory ceiling clearance. This height constraint hence gives us the maximum permissible pendulum length and vertical drop height, thereby directly influencing the achievable impact velocities. To ensure compact size while maintaining functional capability, the pendulum length was fixed at 1900 mm, measured from the pivot point to the center of the impactor mass.

The boundary conditions and height constraints adopted in the design are illustrated schematically in Figure 1. These constraints ensure safe pendulum swing clearance, easy access for operator, and are compatible with standard laboratory infrastructure

Table 1. *Design constraints and boundary conditions adopted for the proposed calibration test rig.*

Parameter	Value	Basis / Source
Maximum allowable rig height	2260 mm	Laboratory ceiling height constraint
Pendulum length (pivot to impactor center)	1900 mm	Compact design requirement
Knee impactor mass	5 kg	AIS-098
Slider mass (low- and high-speed cases)	12 kg	SAE J2876
Knee impact velocity	As prescribed by AIS-098	Standard
Low-speed knee slider velocity	As prescribed by SAE J2876	Standard
High-speed knee slider velocity	As prescribed by SAE J2876	Standard
Pendulum release parameter	Angular displacement (θ)	Design variable
Gravity	9.81 m/s²	Constant

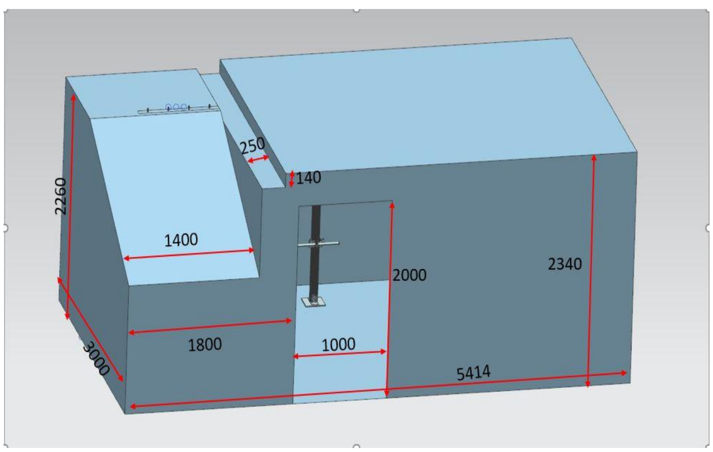

Fig. 1. *Room dimensions and maximum height constraint adopted for the proposed compact knee calibration test rig.*

Standard-Driven Mass and Velocity Constraints

The calibration requirements specified in AIS-098 and SAE J2876 depicts the target mass and velocity range. These parameters were hence treated as standard parameter inputs and not just design variables.

For knee impact calibration, the impactor mass was fixed as given by AIS-098:

- Impactor mass for knee impact calibration: 5 kg

For knee slider calibration, the effective moving mass was given by SAE J2876:

- Slider mass configuration: 12 kg

Further, the target velocities for knee impact and slider calibration were considered directly from the respective standards and were not altered during the design process. Design flexibility was achieved using geometric and kinematic adjustment, primarily by varying pendulum release angles.

Unified Rig Architecture

Based on the defined spatial and standard constraints, a single unified rig architecture was designed capable of supporting both knee impact and slider calibration within a single setup. The overall configuration of the proposed dual mode calibration rig is shown in Figure 2.

The rig consists of a rigid base frame, a vertically oriented pendulum mechanism for knee impact and slider calibration. Both test modes share a common frame, guide system, and knee mounting reference, and thereby minimize alignment variation and eliminate the need for multiple independent test setups. Transition between impact and slider configurations is achieved using minimal mechanical modification, supporting efficient reconfiguration.

SR.NO	PART NAME	MTRL	WT(KG)	QTY
1	BASE PLATE	MS	29.34	1
2	M16X2 INSERT OD 22MM			8
3	IMPACT STAND FRONT PLATE	MS	17.76	1
4	IMAPCT STAND RH AND LH SIDE RIB	MS	9.3	2
5	IMPACT STAND BASE PLATE	MS	15.0275	1
6	KNEE RIGID FIXTURE	MS	3.09	1
7	KNEE MTG SHAFT 1	MS	1.0322	1
8	KNEE MTG SHAFT 2	MS	0.6416	1
9	BOLT M12X1.75X(TL-50) HEX HEAD			4
10	NUT M12X1.75			4
11	PLAIN WASHER ID-13MM			4
12	UPPER STRUCTURE RH AND LH C CHANNEL 125X65	MS	9.33	2
13	UPPER STRUCTURE LH AND RH RECTANGULAR TUBE 100X50	MS	9.06282	2
14	EYE BOLT MTG PLATE LH AND RH	MS	1.6851	2
15	EYE BOLT ID 19MM M6X1			4
16	EYE BOLT NUT M6X1			4
17	BUTTERFLY BOLT M12X1.75 TL-35)			4
18	BUTTERFLY NUT M12X1.75			4
19	ALLEN BOLT M16X2			12

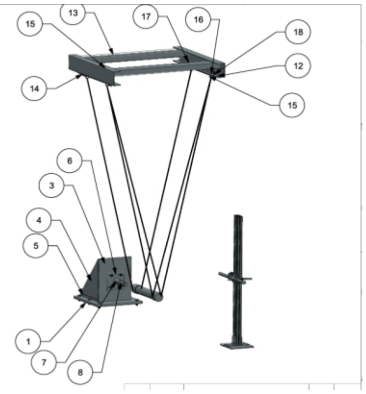

Fig. 2. *Exploded CAD view of the proposed compact dual-mode knee calibration rig showing major structural components, pendulum assembly, knee fixture, and bill of materials mapping.*

Analytical Formulation for Pendulum Based Impact Velocity

Impact Velocity Equation

The knee impact calibration velocity in the proposed rig is calculated using classical pendulum dynamics. As we know that for a pendulum of fixed length L, released from an angular displacement θ, the vertical drop height h of the impactor is given by:

$$h = L(1 - cos\theta) \quad (1)$$

On assuming negligible air resistance and minimal frictional losses at the pivot, conservation of mechanical energy gives us:

$$½\, m\, v^2 = m\, g\, h \quad (2)$$

Substituting Eq. (1) into Eq. (2), we get the analytical expression for the impact velocity v of the pendulum mass:

$$v = \sqrt{}(2\, g\, L\, (1 - cos\theta)) \quad (3)$$

Equation (3) forms the basis for determining the achievable knee impact velocity in the proposed calibration rig for a given pendulum length and controlling the variation through release angle. In the present design, the pendulum length was fixed at L=1.9 m while the release angle θ was varied to achieve standard velocities while respecting the maximum rig height constraint of 2260 mm. The pendulum based impact mechanism and geometric parameters are schematically illustrated in Figure 3.

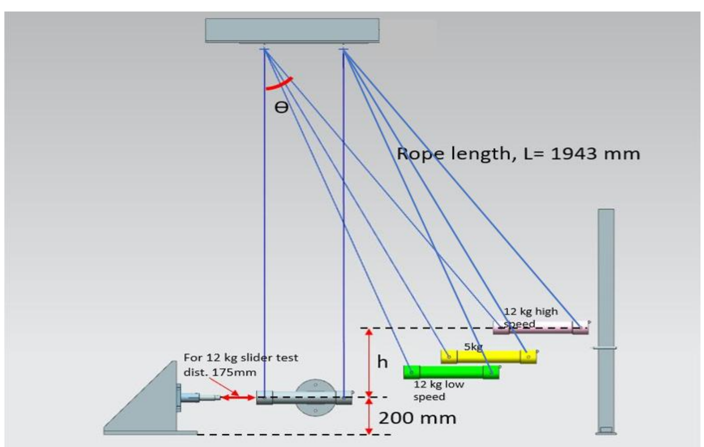

Fig. 3. *Schematic representation of the pendulum based impact mechanism illustrating rope length, release angle (θ), vertical drop height (h), and mass configurations used to achieve standard impact and slider velocities.*

Analytical Determination of Release Angles

The required pendulum release angle for target impact or slider velocity as prescribed by AIS-098 or SAE J2876 can be analytically determined by rearranging the velocity expression given in Eq. (3). Solving Eq. (3) for the release angle θ gives

$$\theta = cos^{-1}(1 - v^2/(2\, g\, L)) \quad (4)$$

Using this formula, release angles were analytically calculated for three calibration cases:

1. Knee impact calibration (5 kg mass),

2. Low speed knee slider calibration (12 kg mass), and
3. High speed knee slider calibration (12 kg mass).

The calculated release heights, release angles, and corresponding velocity ranges used in the present study are summarized in Table 2. These values were further cross checked using CAD/CAE-based dynamic analysis to ensure consistency with the analytical calculations and to validate theoretical compliance with standard velocity conditions.

Table 2. *Calculated release angles and analytically obtained velocities for knee impact and knee slider calibration cases.*

Probe mass (kg)	**Height from ground for release (h, mm)**	**Angle of release (Θ, deg)**	**Velocity Achieved analytically (m/s)**	**Standard velocity required (m/s)**
12 kg (High speed)	581	35.9	2.72 to 2.75	2.7 to 2.8
12 kg (Low Speed)	338	21.4	1.63 to 1.66	1.53 to 1.7
5 kg	422	27.4	2.06 to 2.10	2.07 to 2.13

Knee Slider Calibration Configuration

Even for knee slider calibration, the proposed rig uses the same pendulum dynamics with the mass axis aligned with the tibial axis of the knee assembly. Slider calibration velocities are given by SAE J2876 and are achieved through direct pendulum impact.

The shared guide rails and fixed knee mounting interface ensure consistent alignment between knee impact and slider configurations. The same gravitational energy based analytical model applies to appropriate geometric modification, maintaining coherence between the two calibration modes.

Design Provisions for Repeatability and Compliance

Repetition of tests in this work is addressed through design intent. The unified frame architecture, fixed knee mounting reference, and shared guidance system minimize uncertainty between successive calibration setups.

These design provisions align with the expectations of ISO/IEC 17025. By embedding these requirements at the design stage, the proposed methodology establishes a robust foundation for future prototype development, experimental validation, and uncertainty quantification.

Methodology Summary

In summary, the methodology integrates the maximum constraint conditions, unified structural design, and analytical calculations based on pendulum dynamics to develop a compact unified knee calibration test rig. By fixing standard parameters such as impactor mass and target velocities and adjusting geometric variables such as pendulum release angles analytically within a maximum rig height of 2260 mm and a pendulum length of 1900 mm, the proposed design model achieves mathematical compliance to AIS-098 and SAE J2876.

Results and Discussion

Impact Velocity and Energy Control

The analytical calculations carried out during the design phase of this study confirm that the proposed compact double prupose calibration rig is capable of achieving the target impact velocity range as given by AIS-098 for dummy knee impact calibration. The pendulum length, was fixed by considering enough swing clearance such that the resulting impact velocities fall under the acceptance range defined by the standards.

The key outcome of this study is achieving the required velocity range for calibration modes as mentioned in standards while designing a compact and unified test setup. Conventional knee calibration rigs often rely on large frames to minimise energy losses and dynamic compliance. In contrast, the proposed design demonstrates that controlled impact energy is deliverable without the need for excessive structural size. This indicates that size does not always compromise impact magnitude when appropriate kinematic and structural considerations are incorporated at the design stage.

Repeatability and Measurement Consistency

Ability to repeat tests is a critical requirement for calibration rigs which is meant for ATD certification and routine laboratory use. The unified frame architecture, fixed knee mounting interface, and shared guidance system are required to minimise alignment variation between both the tests and hence ensure high repetiton.

By eliminating the need for separate rigs and repeated alignment between knee impact and slider calibration modes, the proposed design reduces potential sources of variation as a result of operator. Such design driven repeatability is particularly important for laboratories operating under ISO/IEC 17025 accreditation, where consistency is very necessary.

Knee Slider Test Performance

For the knee slider calibration mode, the design calculations owing to the pendulum dynamics indicate that the proposed rig can generate controlled sliding motion with same pendulum rope lengths and velocities while also remaining comliant to SAE J2876 requirements. The shared sled and guide assembly ensures consistent boundary conditions and alignment geometry between the impact and slider configurations.

Integrating both calibration modes within a single frame allows the same reference geometry and guidance system to be used for both tests. From a design point of view, this reduces the chances of parasitic friction, misalignment, or unintended constraints that could influence slider calibration accuracy. The analytical evaluation confirms that the double mode configuration can satisfy slider test requirements without compromising required standard velocities.

Comparison with Conventional Calibration Rigs

Compared to the conventional knee calibration rigs that require large, single function frames, the proposed design achieves equivalent functional capacity within a considerable reduced dimensions. Traditional rigs very huge in size to ensure stiffness and stability, whereas the present design adopts a compact but structurally strong layout to achieve similar performance objectives.

The integrated architecture also simplifies the calibration workflow by simplicating the setup and eliminating the need for multiple dedicated test frames, this results in reduced alignment effort, shorter change time between test modes, and enhance total efficiency. These advantages are significant for research laboratories and smaller testing facilities where space and cost constraints limit access to conventional large calibration equipment.

Implications for Calibration under compliance

The design analysis confirms that the proposed rig satisfies the essential mechanical and kinematic requirements specified in AIS-098 for knee impact calibration and SAE J2876 for knee slider testing. By meeting the required mass, velocity, alignment, and instrumentation constraints using analytical verification, the proposed system provides a practical setup for calibration. This is further complying to the necessary standards.

The unified frame and shared instrumentation layout further enhance consistency and reduce redundancy, supporting efficient calibration workflows. The design also offers a practical approach for laboratories to implement knee calibration capabilities without depending on large, conventional rigs, and as a result improving access and scalability while following the standard constraints.

Discussion Summary

The outcomes of the design calculations and analytical evaluation indicate that a compact, integrated knee calibration rig can be developed to support both knee impact and slider calibration in a single test rig. The proposed work addresses key limitations of existing calibration test rigs comparing characteristics such as compactness and modularity without compromising kinematic or structural requirements. These findings support the feasibility of the proposed concept and provide a strong foundation for future prototype development and experimental validation.

Conclusion

This paper presented the design and analytical as well as theoretical validation of a unified compact calibration test rig capable for performing both the knee impact as well as knee slider calibration in a single integrated frame. This design learns from through the limitations of conventional calibration systems, including large space footprint, single operation, and extensive reconfiguration requirements. The developed rig enables functional integration which is adopted by implementing the laws of pendulum dynamics while also stricIty following the kinematic constraints prescribed in necessary standards.

Analytical formulation as a result of classical pendulum dynamics demonstrated that the proposed rig can achieve the target impact and slider velocities specified by relevant automotive safety standards through controlled variation of pendulum release angle, and impactor mass. For a fixed pendulum length of 1.9 m, the analytically obtained release angles made multiple calibration velocity levels achievable while adhering to the maximum allowable laboratory height constraint of 2260 mm. These results indicate that the unified configuration can meet the required velocity range with predictable and repeatable kinematic behavior by design, without the need for separate calibration setups.

The compact architecture offers a significant reduction in laboratory space requirement and improves operational efficiency by eliminating bulky structures and timely alignment steps associated with unique functional rigs. A tentative cost estimation based on commercially available components and gneral laboratory fabrication principle indicates that the proposed unified compact calibration rig can be quoted at an estimated cost of approximately 12–14k USD. In contrast, conventional single functional knee impact and slider calibration systems typically require a combined investment in the range of 60–90k USD, suggesting a potential cost reduction of approximately 75–85%, in addition to savings in laboratory space and setup complexity.

The analytical results confirm that the proposed design is a cost effective and compact for laboratory use, alternative to conventional calibration infrastructures while preserving alignment accuracy, and velocity control. Future work will focus on prototype development, experimental validation, and assessment to quantify repeatability, energy transfer characteristics, and measurement uncertainty under physical testing conditions.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding publication of this paper.

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