

A Verifiable Methodological Framework for Designing an Instrumented Smart Parallel Bars Apparatus to Estimate the Most Probable Source of Technical Errors

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ABSTRACT

This is a design and methodological study that tackles a common issue when analysing the skills performed at parallel bars in the sport of artistic gymnastics – errors noted in the landing phase do not necessarily indicate the time at which the disturbance occurred. This mistake can be caused by support, swinging, lack of push-off, timing of releasing, tucking or opening. Thus, the paper suggests a framework of a testable and buildable instrumented research parallel bars apparatus which can be adjusted electronically only before the event and includes rail load/motion, high speed video and force platforms under the landing mat all on one time line. The goal is to assess the earliest possible signal that is consistent with the observed error, in the technical stage, based on temporal precedence, mechanical consistency, recurrence across trials, good data quality, and video/expert agreement, but not to make claims of causality. The design allows the gymnast load path to be separated from the electrical gymnast adjustment system with spring loaded mechanical locks and secondary safety pins. It defines initial measurement channels, quality gates, operational evidence-weighting principles, safety requirements and a staircased validation procedure. The start with the somersault double front, tuck, is applied to phase segmentation and to the candidate indicators. Since a 20 cm landing mat not only dampens and propagates information of the impact, center of pressure is only considered a macro-indicator of the landing area and not to reconstruct foot level pressure. Future validation tests are proposed to be conducted by bench calibration, non-human safety testing, content validity assessment, feasibility (reliability) testing and a feasibility sequence A1-B1-B2-A2-T testing after prototype and ethical approval. No claims regarding human performance, diagnostic accuracy or regulatory approval or competitive readiness are made in the present paper. The catch is, where evidence is lacking, this adds a new element of auditable chronological chain of mechanical evidence, instead of just endpoint error interpretation.

Keywords- artistic gymnastics; parallel bars; embedded sensing; sports equipment design; landing mechanics; biomechanical feedback; technical error origin.

I. INTRODUCTION

The three pillars of gymnast's kinesthetic awareness, video and the coach's eye are all important components of training high risk parallel bars skills. But, as significant as they are, these pillars are not always enough to provide a specific diagnosis for when a technical issue became apparent. The loss of balance may be evident on landing on the mat, but may be due to an asymmetric hand push-off, lack of swing velocity, improper release angle or opening up too soon. Therefore, tools are needed that will connect the events of the kinetic chain in time, as opposed to just describing the end product of the skill. The literature closely related to the study's central question can be structured along 4 axes which are overlapping each other. The first relates to the parallel-bar modelling of forces and measurement or estimation of forces from the movement of the rails [1] - [4]. The second is kinematic and biomechanical analysis of the skills and dismounts in parallel-bars, utilizing

high velocity video and modeling the skills to analyse performance and choice of techniques [5-10]. Some other studies have analyzed the kinematics of forward support swings, and conducted a systematic review of previous studies for exercises performed on the parallel bars [29, 30]. The third axis has to do with landing forces, mat impact and measurement of ground-reaction forces in gymnastics [11]-[14]. The fourth is about the biomechanical feedback systems and how video and force information can be incorporated in sport and gymnastics [15]-[17]. On their own these studies demonstrate that each measurement channel is valuable, but do not typically present a clear pathway to combine the rail response, body kinematics and landing mechanics into a single sequential pathway to estimate the earliest possible technical source for a given observed error, particularly with parallel bars. The gap that has been filled by proposed framework is summarized in table 1. The issue is that sensing technology, as it is, is not missing, it's the lack of an explicit and auditable way to synchronize these channels and create a temporal and mechanical chain of evidence, and not be able to take a leap when the evidence is incomplete. This paper is designed to be a study of design and/or methodology. Its offering is a testable specification, not a promise of an effectiveness in training. In this context, "smart" applies to the integration and synchronization of multiple sensors and the auditable rules for weighting and not to AI or machine learning or autonomous diagnostics. The proposed apparatus therefore is not a competitive product and cannot substitute for the human experts and it is just a research platform to help the coach. The main idea is that when the evidence of launching, moving, and landing events is presented in chronological order, it could be easier for the person reviewing the evidence to see if an error went into launching, moving, or landing. Because of this, the framework does not include any language that specifies "causally" why the design is better, claims of unmeasured improvements or suggest regulatory certifications prior to the development of data on prototypes, safety evidence, and validation.

Table 1. Literature map and the gap addressed by the paper.

Study axis	Main contribution	What remains missing for the present question
Rail forces and modeling	Methods and models have estimated rail forces and rail movement on parallel bars [1], [3], [4].	Hand-loading impulses are not usually transformed into a unified interpretation that also incorporates video and landing.
Parallel-bars skill analysis	Video, kinematics, and modeling have examined swings, dismounts, and determinants of performance [5]-[10].	Kinematic description alone does not capture the load on each rail and landing forces on the same synchronized timeline.
Landing forces and mat effects	Gymnastics studies have examined mat effects, landing impact, and ground-reaction forces [11]-[14].	Landing describes the endpoint but cannot alone determine whether the disturbance began earlier in push-off, release, or flight.
Biomechanical feedback	Video-force integration and biomechanical feedback have been used in sport and gymnastics [15]-[17].	Within the reviewed literature, no explicit parallel-bars logic was identified that ranks the earliest plausible technical origin while retaining a formal unresolved option.
Contribution of this paper	Rail signals, video, and landing platforms are placed within one synchronization, safety, and validation framework.	The contribution is intended as a falsifiable methodological framework, not validated diagnostic accuracy or approval before prototype construction.

II. STUDY OBJECTIVES AND QUESTIONS

The study's goal is to develop a methodological framework based on instrumented research parallel bars apparatus, which allow the estimation of the most probable technical origin of errors, and to be verified by the dismount of the tucked double front somersault as an initial application. The paper specifies requirements in four layers that are interrelated: apparatus requirements, measurement and synchronization quality, weighting rules for the origin of error and validity/safety rules. The three research questions are used to frame the apparatus: (1) What minimum engineering and measurement requirements would make the apparatus suitable for research use? (2) How can indicators from the rails, video and landing

be derived without breaking down the skill to a value? (3) What statistical and methodological approach could minimize the potential for over-interpretation in the future when small samples of elite gymnasts will be used in a later validation?

III. METHODOLOGY

3.1 Study Design

The design of the study is divided in three phases. The first phase involves the development of apparatus specifications, measurement architecture and safety requirements. In the second phase, bench and mechanical testing of the apparatus with no gymnasts. After gaining independent ethical approval and completion of safety tests, the third phase will involve a multiple-case feasibility study of adult elite gymnasts who have already mastered the skill. There are two principles of governance. At this stage the apparatus is not claimed as a FIG/World Gymnastics apparatus, but is a research apparatus. Second, in any attempt to understand the origin of the error, there should be temporal precedence, mechanical consistency, a reoccurrence of the error, and good data quality, with an explicit “unresolved” outcome when the data is conflictive or weak. This interpretation is then an inference of the operation that is subject to review and not proof of causality or an independent diagnosis. The framework also provides some guidelines for situations where the design is deemed to be a failure. It can only be successful methodologically if the prototype that is realized is able to isolate the gymnast load path from the electrical adjustment path, to create calibratable and synchronized signals, to generate indicators to be reproduced with an acceptable stability and to give an interpretation that can be audited by independent experts. It fails when synchronisation is insufficient, noise in the measurement is greater than the technical changes of interest, or the decision logic is unable to withhold a decision, where channels conflict.

Table 2. Phases of apparatus development and validation.

Step	Function	Transition condition
Specification	Define dimensions, loads, sensors, adjustment limits, and intended use.	Independent engineering review and an initial risk register.
Bench testing	Test calibration of force, deformation, acceleration, and inter-channel synchronization.	Measurement error and delay within predefined limits.
Mechanical safety	Test locks, secondary locking, power loss, and non-human proof loads.	No structural failure or unintended motion under load.
Low-risk movements	Use simple low-risk movements to evaluate signal stability before high-load skills.	Stable acquisition and clear stop criteria.
Future human study	Apply the A1-B1-B2-A2-T feasibility sequence; stagger onset between athletes when feasible.	Ethics approval, informed consent, emergency/stop plan, and closure of all non-human safety tests.

3.2 Description of the Proposed Apparatus

The concept of the framework is directed towards the design of a research parallel bars apparatus, which can electronically adapted to a height and width in accordance with training limits, but still remain competitive if necessary. The actuators are designed to do nothing more than preperformance adjustments and allow the dynamic loads during the skill to be handled by spring loaded mechanical locks and secondary pins. Intended safe state is considered to be when actuators are stopped, load-bearing members are mechanically locked and there are no movements or self-starting after power loss and/or load is detected on the apparatus, until a deliberate reset procedure is completed. The separation is at the heart of the suggested architecture – electrical motion is used to set up the system, while the mechanical structure is used to transport the gymnast during performance. The design identifies three layers: (1) a mechanical structure that can carry the load, (2) a layer for measurements without affecting the gripping surface and (3) a layer for control which is not part of the dynamic load path. The rail can have a composite core, or can be a continuous wooden contact surface similar to a competition rail. Full-bridge strain gauges can be located in protected lower recesses, force/moment transducers can be installed at joints or support points and a triaxial accelerometer can be installed under a rail or near its end. After installation, the accuracy of the measurement and the usable bandwidth on the sensor must be determined and not assumed from the sensor datasheet as the installed response can be affected by nonlinearity, cross axis sensitivity, humidity, magnesium, rail vibration and mounting conditions. The dimensions for the rails and the apparatus height/spacing and the landing should be taken from the appropriate 2026 World Gymnastics apparatus norms [18] and [19]. Being similar to those dimensions does not mean that it is certified for

competition. If the parallel-bars environment is reproduced, a 200 mm landing-mat assembly should be used as the base assembly; if a supplementary mat is used during training, it should be noted as part of the measurement configuration as it may alter the way the force is transmitted to the underlying platform, for example if a 100 mm supplementary mat is used. The application of ISO 12100, ISO 13849-1 and IEC 60204-1 [20]–[22] are applied merely as a design reference and not as evidence that the apparatus has been built and certified.



Figure 1. Overall architecture of the proposed instrumented smart parallel bars apparatus. Conceptual schematic only; it does not represent a manufactured prototype.

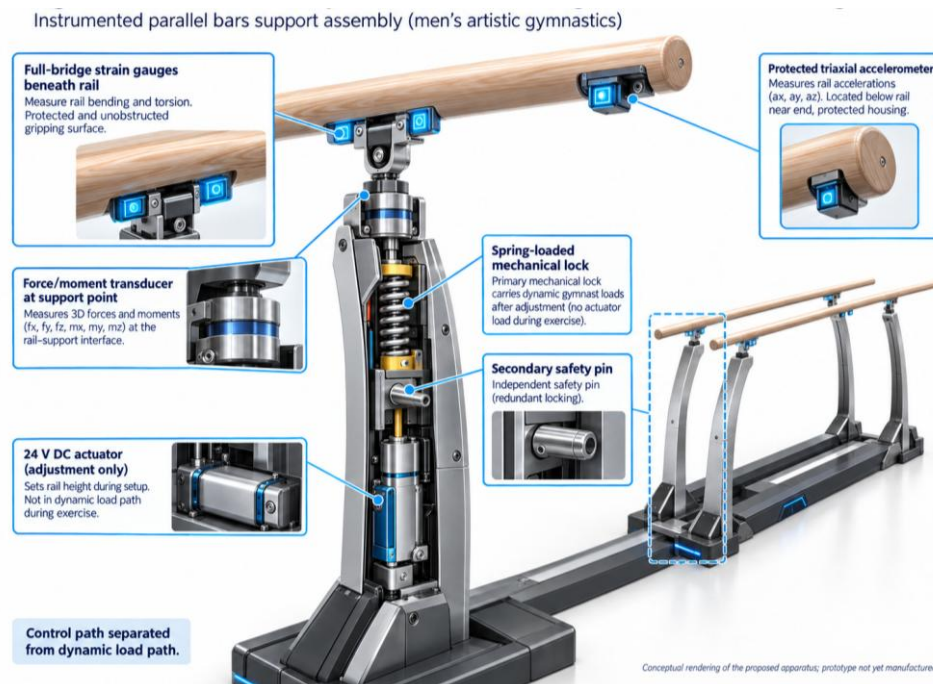


Figure 2. Conceptual mechanical load path and redundant locking mechanism. Dynamic skill loads are intended to be carried by the mechanical structure rather than the adjustment actuator.

Table 3. Proposed minimum technical specifications before transition to human testing.

Domain	Proposed minimum	Verification method
Rail and gripping surface	Wooden upper contact surface or competition-like surface; no exposed measurement components; protection from moisture, magnesium, and vibration.	Dimensional/friction checks, visual inspection, and pre-session deflection/frequency check.
Rail load and deformation	Full-bridge strain gauges beneath the rail and force/moment transducers at support points; measurement range set after non-human loading.	Static and dynamic calibration for linearity, hysteresis, cross-axis sensitivity, and error smaller than the targeted technical change.
Rail acceleration	Protected triaxial accelerometer below the rail or near its end; sampling rate set after bandwidth and phase testing; rates up to about 5 kHz may be examined if justified by installed response.	Sensitivity, phase, bandwidth, anti-aliasing filter, and video-event alignment checks.
Adjustment and locking	Low-voltage actuators for adjustment only (e.g., 24 V DC), with spring-loaded mechanical locks and secondary pins that carry the load after positioning and inhibit motion when loaded.	Power-loss, lock-engagement, column-mismatch, emergency-stop, safe-state, and no-auto-restart tests before human use.
Synchronization and video	Common hardware trigger and camera-visible LED; initial high-speed video range of 240-480 frames/s, reviewed after event-labeling tests.	Quantify synchronization and reprojection error; reject source estimation when release, opening, or contact is occluded.
Landing	One or two force platforms beneath a 200 mm base landing-mat assembly; document any additional 100 mm training mat and characterize the complete stack.	Calibrate/characterize the mat-platform system; estimate COP, force-peak timing, and bilateral distribution with declared uncertainty.

3.3 Measurement and Synchronization System

The proposed system will work on the basis of integration of the rapid signals received from the rail, high speed video and two force platforms, which are placed under the landing mat. None of the channels is considered as the single evidence; channels are combined together in a single time line and the beginning of the deviation and the direction of the deviation are identified. It is proposed to use a layer of AI-assisted analysis in the case of synchronous video tracking, feature extraction, screening of signal quality and pattern support to rail, video and landing channel. AI support is not a substitute for the quality gates mentioned in this paper, for an expert check, or for the auditable decision logic described in this paper and therefore does not act as an independent diagnostic system. Predefined data-quality gates are applied before generating any interpretation. It would be inappropriate to classify a trial as a probable-source when a sensor is saturated, the number of critical frames is lost, the synchronization error is greater than what the sensor claims, release/opening/contact is occluded, or the baseline drift makes between-trial differences as large as the measurement noise. After measurement of the effective bandwidth, phase response, noise characteristics and anti-aliasing requirements of the installed system, the final sampling rate is then determined. The values in Table 4 are preliminary design targets and not experimental tested final values. Extra care should be taken when landing on the landing mat. The 20 cm thick gymnastics landing mat buffers and disperses impact information to a force platform [12]-[14]. Thus peak vertical ground reaction force, time to peak, bilateral distribution and the center-of-pressure (COP) behavior can be recorded, but COP is interpreted as simply a macro-indicator of landing zone and global loading pattern (as opposed to simply being a reconstruction of the foot level pressure beneath the mat). For validation the complete mat-platform setup has to be characterized.

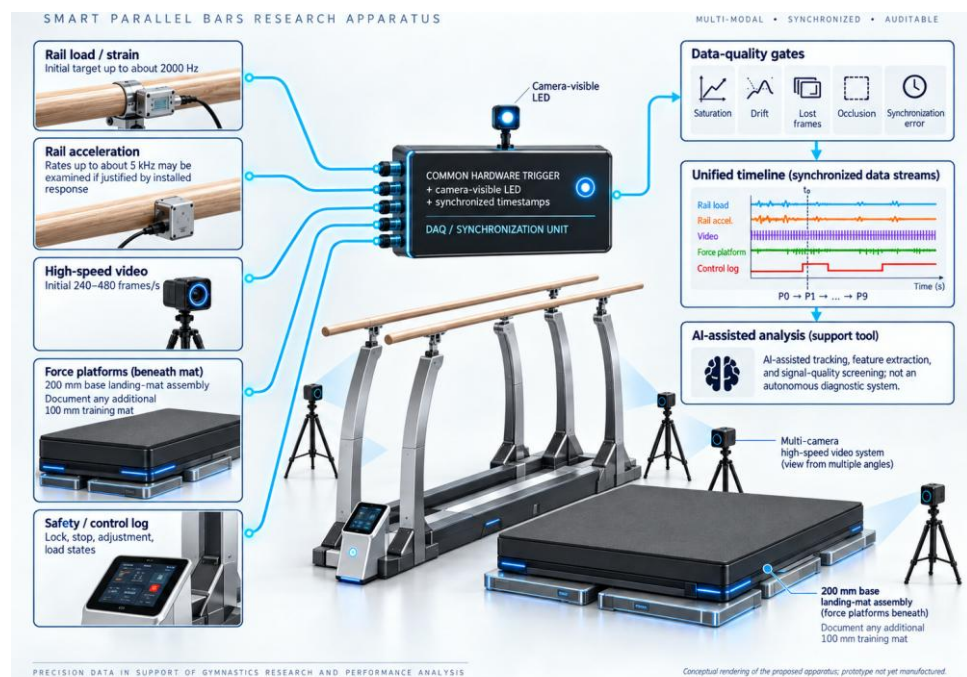


Figure 3. Integrated measurement and synchronization architecture combining rail signals, high-speed video, landing force platforms, and a common acquisition timeline.

Table 4. Measurement channels and their research function.

Channel	Initial target rate / resolution	Data-quality condition
Rail load/strain	Initial target up to about 2000 Hz; final rate set after measuring push-off bandwidth, with adequate oversampling, anti-aliasing, and conversion to SI units after calibration.	No saturation or influential drift; do not use peaks outside the calibrated range.
Rail acceleration	Initial design target up to about 5000 Hz when needed; confirm or reduce after installed bandwidth, phase, and noise testing.	Do not interpret brief vibration technically until sensor response, phase, mounting, and rail structural behavior are characterized.
High-speed video	Initial 240-480 frames/s; volumetric calibration for 3D analysis or explicit justification for 2D; rate reviewed against event-timing precision.	Reject 3D analysis when occlusion occurs or reprojection error exceeds its prespecified limit.
Force platforms beneath mat	Sampling rate set after testing the full mat configuration and expected force range.	Do not report landing peaks when samples are lost or COP exits the valid measurement region.
Safety/control log	Timestamp lock, stop, adjustment, and load states.	Any locking failure or emergency stop excludes the trial from performance interpretation and is logged as a safety event.

3.4 Applied Skill and Phase Segmentation

The tucked double front somersault dismount was chosen as it requires a good final support, a good sense of timing for the release, quick rotation and a short time on the floor before landing. The framework divides up every trial into easily reproducible and markable events from stable support to landing. The biomechanical principles of event-identification from the changes in load, rail acceleration and synchronized video are used to determine phase boundaries. The segmentation does not mean that phases are independent, but rather offers a systematic ticking in time to follow the propagation of the

disturbance from support/release to flight and landing. The labels of the events should be independent and their uncertainty should be re-examinable by independent analysts.

Table 5. Skill phases and data sources.

Phase	Event	Measurement channels	Derived indicator
P0	Stable preparatory support	Rail load and video	Individual baseline for force and symmetry.
P1	Final swing	Rail motion and video	Velocity direction and swing-phase change.
P2	Preparation for release	Rail and video	Proximity to the push-off/release window.
P3	Final push-off impulse	Rail load and acceleration	Push-off impulse and between-side asymmetry.
P4	Loss of contact / release	Synchronized rail and video	Release time and body configuration at take-off.
P5-P7	Flight, tuck, and maximal rotation	Video and movement model	Flight height, angular velocity, and tuck consistency.
P8	Opening before contact	Video	Opening timing relative to final body configuration.
P9	Ground contact and stabilization	Force platforms and video	Landing forces, COP macro-pattern, and stabilization.



Figure 4. Proposed segmentation of the tucked double front somersault dismount into measurable phases P0-P9. The illustration defines event-labeling structure rather than experimental results.

3.5 Decision Model for Estimating the Most Probable Source of Error

One of three interpretive results are produced by the system: probable source, possible source, or unresolved. Four conditions for a probability-like operational score are mandatory: temporal precedence, mechanical consistency, recurrence of the score from trial to trial and quality of the data. The score is not a standardised diagnostic probability and should not be used as evidence of a candidate phase as the cause of the error. A preliminary operational evidence score (0-100) could be scored during the next validation after the quality gates are passed. The first suggested candidates weights for sensitivity testing is 25% temporal precedence, 25% mechanical consistency, 20% recurrence, 15% data quality, and 15% video/expert agreement. Candidates that score ≥ 70 and < 80 will be classified as 'probable source' and those that score 50-69 will be classified as 'possible source', and below 50 or if failing any mandatory gate, classified as 'unresolved'. These are all values which are clearly temporary. Prior to any applied use, they should be preregistered for the validation study, should be varied

in sensitivity analyses and should be subjected to leave-one-component-out analyses. The decision record must also include the alternative explanation, and why a decision of not resolving was or was not chosen.

Table 6. Examples of candidate indicators for testing the error source.

Indicator	Initial operational definition	Potential interpretation
Hand-load asymmetry	$AI = F1-F2 /(F1+F2) \times 100$ within a predefined push-off window; compare with the individual baseline and do not compute when total force is below a noise-derived quality threshold.	A recurrent deviation may precede flight-axis drift or unwanted rotation; assess together with impulse asymmetry rather than as a stand-alone value.
Release time	Interval between the push-off peak and loss of contact, interpreted with body position and take-off velocity.	Early or late release may alter trajectory and flight height.
Post-push rail vibration	Peak acceleration or RMS/vibration energy within a declared time window after characterization of bandwidth, phase, and relevant natural frequencies.	Descriptive mechanical indicator initially; do not attribute it to uncoordinated push-off or stiffness until repeated technical association is validated.
Flight quality	Flight time, approximate height, angular velocity, and tuck/opening timing from video.	Describes transfer from support into rotation before landing.
Landing indicator	pVGRF normalized to body weight, time to peak, COP macro-trajectory, and bilateral distribution.	Helps distinguish a predominantly landing-phase error from a disturbance that appeared earlier.

Figure 5.
Decision model for
estimating the most
probable source of
technical error.



Figure 5. Decision logic for ranking the most probable technical origin while retaining possible-source and unresolved outcomes. Thresholds and weights are provisional design parameters for later validation.

3.6 Validity and Reliability Plan

Content validation starts with a panel of gymnastics, biomechanics and equipment engineering experts. Reliability is assessed at three levels: calibration stability of the sensor, synchronization consistency and intra-athlete indicator stability. Expert selection criteria, panel size, distribution of discipline of experts, and experience should be determined prior to data collection. There is a need to critically assess each candidate indicator from the point of view of clarity, biomechanics and potential for misinterpretation. CVI may be item level or scale level; the following values used only as initial guidance when

the assumptions of the method are met: I-CVI ≥ 0.78 and S-CVI/Ave ≥ 0.90 [24]. CVC will then compare predefined trial categories (such as technically acceptable, under-rotated, tilted, and early-opening trials) without training a small sample for closed diagnostic model. Reliability should encompass repeated calibration of sensors, synchronization repeatability, interrater agreement (event labelling) and within athlete stability under similar trials. In the case of continuous measures, with independent analyst labeling, a two-way ICC for absolute agreement should be chosen and reported with model, unit of analysis, and CI [25]. Categorical judgments should be based on a weighted kappa or other coefficient that is suitable for the number of raters and number of categories. Determine if an apparent change is greater than measurement noise using coefficient of variation or standard error of measurement.

Table 7. Validation, validity, and reliability matrix.

Domain	Test	Output	Initial transition criterion
Calibration	Known loads/deformations spanning the intended operating range.	Bias, RMSE, and agreement limits.	Calibration error clearly smaller than the smallest targeted technical change; 5% of calibrated range may be used only as an initial design ceiling until the final criterion is fixed.
Synchronization	Reference pulse visible in video and recorded on analog/digital channels.	Mean delay and timestamp dispersion.	Initial engineering target: absolute timing error ≤ 5 ms and repeated jitter ≤ 2 ms, provided bench testing confirms this is sufficient to separate critical events.
Safety	Power loss, lock test, non-human load, and emergency stop.	Lock state, stop log, and verified load path.	Zero structural failure or unintended adjustment motion, with lock stability under a declared safety factor.
Expert agreement	Blinded repeated assessment of predefined trial categories.	ICC for continuous variables; appropriate weighted kappa for categorical judgments; confidence intervals.	For continuous variables, ICC point estimate ≥ 0.75 as a provisional target with its confidence interval; categorical kappa criterion set separately before data collection.
Within-athlete reliability	Comparable-quality trials across repeated sessions.	CV and standard error of measurement.	CV $\leq 10\%$ as an initial target, or preferably SEM below the smallest training-relevant change defined a priori.

3.7 Proposed Future Human Validation Protocol

The next human study is a multiple baseline feasibility design with adult elite gymnasts. The sequence involves a baseline (A1) in which no feedback is provided, presentation of specific indicators (B1), interpretation of errors in relation to the specific indicators (B2), feedback fading (A2) and a brief follow-up retention (T). The future feasibility sample consists of 6-10 elite gymnasts (18 years or older) who regularly practice the dismounts in question as part of their safe training routines. For validation, no athlete should be asked to learn a new high risk skill. Intervention start times should be staggered between athletes where possible to minimize confounding due to time, practice or learning. Order of trials, rest periods, perceived exertion, fatigue and pain should be recorded since this could otherwise be interpreted as an effect of the apparatus and/or feedback. Prior to human testing, stop rules need to be defined. These are pain, more than two consecutive trials of a decrease in predetermined safety parameters, locking or synchronization failure, reflex of the athlete/coach, or any unforeseen event. Only following successful non-human load testing, stable primary and secondary locks, disabled adjustment under load, acceptable synchronization accuracy, emergency readiness, informed consent and ethics approval (all

with an independent checklist), is progression to human performance allowed. Documentation and retesting is needed for any engineering modification prior to subsequent data collection.



Figure 6. Proposed A1-B1-B2-A2-T feasibility sequence after prototype approval and completion of non-human safety testing. No human-study results are reported in the present paper.

3.8 Statistical Analysis Plan for Future Validation

Different types of linear or non-linear regressions are used to analyse the calibrations and results are presented in the form of RMSE and bias. Only quantitative comparisons of two methods for measuring the same variable are done using Bland-Altman analysis [26]. For a subsequent human study the effect of the feedback is displayed as a time series for each gymnast and effect sizes are calculated for each phase using indices appropriate for single-case studies, e.g., Tau-U [28]. The analysis plan must be determined prior to data collection and include definitions of events, digital filtering, analysis windows, rules for exclusion of trials, weights assigned to evidence and limits for classification. A prespecified sensitivity analysis should adjust weights and thresholds over ranges of weights and thresholds that are considered plausible, and include the frequency of the different classification results. A leave-one-channel (or leave-one-component-out) analysis should be done to see if the decision is dominated by a single signal source. Trials within a gymnast are not independent samples and reporting will start at the level of the athlete and either lead to cautious descriptive/hierarchical summary that takes into account within-athlete clustering. The repeated-measures design is a feasibility, decision-validity design; not a treatment-superiority trial. By itself a p-value should not be the benchmark of success, especially in a small elite sample [27]. Instead, feasibility, validity of measures, reliability, confidence intervals, effect sizes (as applicable), and practicality of the apparatus to differentiate technically meaningful change from measurement error are prioritized. Only sensitivity and specificity can be reported if there is an independent and defensible reference standard.

3.9 Limits of Interpretation and Transition to Empirical Evidence

The findings of the current paper are confined to internal consistency and tests of the design structure. The manuscript does not allow for claims of diagnostic accuracy, training effectiveness, human safety or readiness for competition to be made prior to building of a prototype, calibration, mechanical testing, and evaluation using proper validation information. Future studies need to differentiate three levels of evidence: apparatus validity, indicator reliability and feasibility/usefulness of biomechanical feedback. If the framework is not able to distinguish between the important temporal events, when uncertainty intervals are too large to make any meaningful interpretation, or when the framework states that the source is probable when the channels conflict or the signal is poor, then the framework should be considered as unsupported. The scientifically acceptable output for weak, conflicting or non-recurrent data is “unresolved.” All sampling rates, acceptance limits, score weights and thresholds used in the present paper, that have not been optimized, are design targets or initial operational parameters.

IV. DESIGN OUTPUTS AND VALIDATION REQUIREMENTS

The proposed design provides five verifiable outputs: 1) an apparatus architecture which separates load path from the actuators, 2) a synchronized measurement system, 3) a phase segmentation logic, 4) a probability-like operational model with evidence and uncertainty, and 5) data-quality rules, eliminating unjustified estimations. These are design outputs and validations requirements, NOT human outcomes, NOT estimates of diagnostic accuracy. Each of these can be refuted by a

pre-established criterion in the process of calibration, synchronization assessment, mechanical safety testing, reliability testing, expert agreement or sensitivity analysis. Table 8 lists the information that should be reported in the event the corresponding validation stage has been performed.

Table 8. Validation outputs to be reported when the corresponding study stage is executed.

Domain	Information to report	Interpretation condition
Calibration	Measurement error, bias, agreement limits, and range used.	Error below the smallest targeted technical change, with documented loads/deformations.
Synchronization	Channel delay and timestamp dispersion at start and end of acquisition.	Precision sufficient to distinguish push-off, release, opening, and landing without reversing their temporal order.
Reliability/agreement	ICC for continuous measures, kappa for categorical judgments, CV, SEM, and confidence intervals.	Reliability adequate to interpret between-phase differences; otherwise declare the indicator not ready.
Decision model	Operational evidence score, supporting channels, alternatives, unresolved proportion, and weight/threshold sensitivity results.	Every classification states supporting evidence, alternative explanation, and reason for not selecting unresolved; score is not treated as diagnostic probability before calibration.
Safety	Every stop, fault, pain event, objection, or engineering modification.	Zero structural failure or unintended adjustment motion during performance, with stop decisions documented.
Data quality	Sensor saturation, frame loss, video occlusion, baseline drift, and synchronization status.	Source estimation fails when a mandatory gate fails; the trial is marked unresolved or excluded.



Figure 7. Integrated workflow from design requirements and bench validation to synchronized acquisition, quality gates, evidence weighting, and auditable reporting.

V. DISCUSSION

The apparatus, the motion and the landing are normally thought of separately and the science value of the framework comes from combining these three aspects. Traditional analysis often begins at the video or landing result, but the question of inter-channel synchronization is: Was the deviation just at landing or did there need to be a measurable change in push-off, release or flight? In recent times, some parallel-bars biomechanics has confirmed the need to focus attention on the

biomechanics of the events that lead to the final result, and to relate biomechanics to the choice of techniques [9] [10]. It is not novel to have just one sensor, a force platform or a video system, these are well known in the literature. The literature surveyed has included proposals for their auditable incorporation via five elements: separation of the dynamic load path from electrical actuators, synchronisation of rail/video/landing data, labelling of events per phase, an operational event-weighting rule allowing for an “unresolved” result, and explicit data-quality gates with prescribed failure conditions. This formulation helps to minimize over-claiming and renders the framework testable and falsifiable. Significant restrictions are made clear. There is no prototype built, no structural load and certification testing is done and no human data are obtained. These sampling rates, acceptance thresholds and evidence-score weights are then initial targets to be tested during bench testing and sensitivity analysis and are not optimal and generalizable. Elite-gymnast samples are of necessity small, and further answers to feedback may be influenced by coaching, expertise, fear, fatigue and order of trials. There can be changes in force transmission due to landing mats and rail vibration can be due to a structure or mounting rather than a technical error. However, these are not necessarily evidence gaps that render a design paper useless, if they are declared as transition conditions. This current claim is not one that requires empirical proof to be completed, it is a design-and-validation claim.

VI. ETHICAL AND SAFETY CONSIDERATIONS

No human trials will begin until an independent moral review has been obtained, a documented engineering inspection, an emergency plan, informed consent and the right to withdraw without penalty are in effect. No feedback should be given that will encourage a continuation of high risk performance when pain, excessive fatigue or decreasing quality is present. Video data need special protection, as names can be redacted, but the athlete's identity still can be easily recognized. As such, the risk analysis in Table 9 is only a Pre-FMEA. It must be translated into a prototype specific FMEA before construction and human use, documenting the severity of failure, occurrence, detectability, residual risk, control measures to be assumed and documented verification tests. Don't assign a numerical risk-priority score until components and use environment are established.

Table 9. Preliminary risk analysis (Pre-FMEA) before human use; to be expanded into a prototype-specific FMEA.

Hazard / failure mode	Potential effect	Proposed control	Verification / acceptance criterion
Adjustment with a person or load present	Impact or loss of balance	Inhibit motion when load is detected; hold-to-run enable; low speed; emergency stop.	No unintended motion during fault-injection tests.
Power loss or lock not engaged	Column drop or transfer of load to actuator	Spring-loaded lock, secondary pin, two independent lock-state sensors, and prevention of automatic motion after power restoration.	Successful documented power-off/restart and non-human load cycles with the load remaining on the mechanical structure.
Column position mismatch	Rail tilt or mechanical binding	Independent position sensing, mismatch limit, and current monitoring.	Safe stop state when a deliberate mismatch is introduced.
Rail or attachment fatigue/fracture	Fall or injury	Structural analysis, fatigue/proof testing, and pre-session inspection.	Independent engineering review before any human use.
Incorrect analytical interpretation	Inappropriate training modification	Keep coach in the loop; show evidence score and alternatives; allow unresolved; block decisions when a quality gate fails.	Expert agreement, declared performance limits, and sensitivity analysis before feedback is used for training decisions.
Identity disclosure from video	Privacy harm	Encryption, coded identifiers, separation of identity key, and restricted access.	Access audit and deletion/retention plan consistent with ethics approval and consent.

Hazard / failure mode	Potential effect	Proposed control	Verification / acceptance criterion
Synchronization failure or sensor saturation/drift	Incorrect temporal ordering or misleading source estimate	Common synchronization pulse, pre/post session checks, saturation/drift monitoring, and a quality gate that stops estimation.	Exclude the trial or mark unresolved when timing limit is exceeded or a signal leaves the calibrated range.

Range of athlete body mass and/or apparatus adjustment range shows prototype design boundaries only and is not meant to be permission for use. None of the gymnasts, from beginners to experts, should use the prototype until non-human load tests, lock verification tests, load-detection interlocks and automatic/human stop procedures have been performed and approved.

VII. CONCLUSION

The research seeks to develop a design and methodological framework for a smart parallel bars apparatus which, once built, can be validated and used to change error interpretation from a final observation to an auditable time line of mechanical evidence. The essence of the framework is that load and control paths are separated, synchronization is required, indicators are reproducible and quality gates are used to limit decisions based on falsifiable criteria. The concept doesn't repeat individual pieces of research on sensing or landing force research, rather, it does what science does and arranges individual research points into a testable series of steps, which sometimes end with the conclusion that the evidence is inconclusive and it is more defensible to conclude that it is "unresolved." The suggested numerical weights and thresholds are initial operational values which need to be evaluated for sensitivity and calibrated before use. Prototype manufacture, bench and non-human safety testing, and an ethically approved validation study, are required to make experimental judgements about diagnostic accuracy, human safety, and training effect of feedback.

DECLARATIONS

Funding: The authors declare that no external funding was received for this work.

Conflicts of Interest: The authors declare no conflicts of interest.

Ethics: This version contains no participant data. Any subsequent human application requires written ethical approval and informed consent.

Data Availability: No raw participant dataset exists for this design study. When the framework is implemented, calibration files, event-labeling rules, indicator-calculation templates, and appropriately de-identified validation data may be shared in accordance with ethics approval and consent.

Content Responsibility: The authors are solely responsible for the scientific formulation and final material of the research.

LIST OF SYMBOLS AND ABBREVIATIONS

Symbol / abbreviation	Meaning
AI	Asymmetry index
COP	Center of pressure
CVI	Content Validity Index
CV	Coefficient of variation
DAQ	Data acquisition
FMEA	Failure Mode and Effects Analysis
ICC	Intraclass correlation coefficient
pVGRF	Peak vertical ground-reaction force
RMSE	Root mean square error
RMS	Root mean square

Symbol / abbreviation	Meaning
SEM	Standard error of measurement
SI	International System of Units
SNR	Signal-to-noise ratio
Tau-U	Nonoverlap-and-trend effect-size index for single-case research

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