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Sensitivity of Modeled L5–S1 Joint Reaction to Virtual Hand-Wrench Translation During a Squat: A Single-Trial OpenSim Study

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Research Article

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Abstract

Purpose.

To quantify how a prescribed virtual translation of hand-applied external wrenches changes the modeled L5–S1 joint-reaction resultant when the measured kinematics and ground reactions of a squat trial are held fixed.

Methods.

A single two-handed, 7-kg box-squat trial (participant P2; FATLS APP1 model) was processed using OpenSim 4.4.1. A free moment equal to $\Delta M = r \times F$ was added while preserving the recorded hand-force vectors, application points, kinematics, and ground reactions. Fourteen accepted model conditions evaluated bilateral global-X (± 50 and ± 100 mm), global-Z (± 50 mm), pelvis-axis (+ 50 mm), unilateral X − 50 mm offsets, and reserve-actuator scaling. Outcomes were descriptive and model-specific.

Results.

The baseline peak resultant was 5,643.59 N. X − 50 and X + 50 mm altered that peak by + 88.38 and − 88.39 N; X − 100 and X + 100 mm altered it by + 176.79 and − 177.11 N. The five-point global-X response was nearly linear (descriptive $R^2 = 0.999999$). Left- and right-hand X − 50 mm changes were + 44.08 and + 44.29 N, with an additivity index of 5.90×10^{-5}. Reserve-scale slope ratios ranged from 0.970 to 1.042. The baseline residual-moment quality ratio exceeded the adopted reference.

Conclusion.

The analysis demonstrates an internally consistent virtual-wrench sensitivity for one fixed-input model instance. It neither estimates physical load relocation nor provides evidence about disc/contact forces, injury risk, other squat techniques, or population-level effects.

Introduction

The placement of a carried load changes external moments and can change posture, movement strategy, and muscle recruitment. Comparisons across squat variants therefore mix changes in the applied load with adaptations in kinematics, contact and force sharing. Experimental comparisons between squat techniques (Gullett et al. 2009; Goršič et al. 2024) cannot, by themselves, isolate the response of a musculoskeletal model to one precisely specified change in its external wrench.

Musculoskeletal simulations enable controlled computational perturbations but require careful distinctions between modeled reactions, actual internal tissue loading and causal interpretations (Delp

et al. 2007; Seth et al. 2018; Hicks et al. 2015). The FATLS model family supports two-handed load interactions and articulated spinal modeling (Akhavanfar et al. 2022, 2024). For the locally available 7-kg box-squat example, the original model and measured trial were held fixed while the moment component of the external hand wrench was changed by a prescribed virtual translation.

The methodological contribution is a bounded, auditable implementation and sensitivity benchmark—not a new physical lifting technique or an estimate of load-position effects in people. We evaluated (i) dose and sign consistency across bilateral X perturbations; (ii) directional, pelvis-axis and unilateral implementation checks; and (iii) robustness to reserve-actuator scaling, while reporting residual demand as a constraint on interpretation. No across-subject hypothesis test was planned.

Methods

Study design, source trial and software

This deterministic single-trial technical study used participant P2's two-handed Squat-7 7-kg box-squat example provided in the FATLS package, with the APP1 full-body OpenSim formulation (Akhavanfar et al. 2022, 2024). The original source tree was not modified. Calculations used versioned work copies and OpenSim 4.4.1, build 2023-07-13-a6f1af5. The available local distribution provided no additional comparable squat repetitions, participants or load conditions; thus, the results characterize one model/trial instance without sampling-based inference.

Virtual hand-wrench perturbation

The measured global hand-force vector F and its original application point were retained. For each specified virtual offset r, a free moment $\Delta M = r \times F$ was added to the corresponding hand wrench. A global-X offset $r = (dx, 0, 0)$ gives $\Delta M = (0, -dxFz, dxFy)$; a global-Z offset uses $r = (0, 0, dz)$. For the pelvis-axis check, r followed the time-varying horizontal projection of the baseline pelvis local + x axis; a positive displacement was defined by the model as anterior in that local frame. This input transformation is not the mechanical relocation of an actual box or bar; no contact geometry, mass/inertia, kinematics, ground reactions, force vectors or measured hand application points were changed (Fig. 1).

Input checks required identical time arrays, measured hand-force vectors and application points, with wrench-identity error ≤ 10^{-12} N·m.

Conditions, primary outcome and acceptance checks

Conditions, primary outcome and acceptance checks
The 14 accepted analyses comprised baseline; bilateral X ± 50 mm and X ± 100 mm; bilateral Z ± 50 mm; pelvis-axis + 50 mm; unilateral left and right X − 50 mm; and baseline/X − 50 mm at 0.5× and 2× reserve-actuator optimal-force scales (Table 1). Every accepted condition completed Static Optimization and

Joint Reaction with exit code zero, 97 and 379 output rows respectively, final time 5.05663276 s, finite values and matching Joint Reaction time grids.

The primary outcome was the Euclidean resultant $|F| = \sqrt{(fx^2 + fy^2 + fz^2)}$ for L5_S1_IVDjnt_on_lumbar5_in_lumbar5, i.e., the reaction on lumbar5 expressed in the lumbar5 coordinate system. This quantity must not be equated to intervertebral disc pressure, disc contact force, or directly measured anatomical compression/shear. Conditional peak change was max(|F|condition) − max(|F|baseline), with a matched-time check at the first baseline-peak sample, $t^* = 2.04831146$ s. The complete time grid was used for peak outcomes. Boundary-sensitive metrics were also checked on an interior grid excluding the first and last samples.

Table 1
Accepted computational conditions and planned implementation checks

Block	Condition(s)	Purpose
Reference	Baseline	Unmodified APP1 hand-wrench input
Primary X	X − 50, X + 50, X − 100, X + 100	Dose response and opposite-sign response
Orthogonal direction	Z − 50, Z + 50	Direction-specific input check
Anatomical frame	Pelvis + 50	Pelvis-axis one-sided implementation check
Unilateral	Left X − 50, right X − 50	Bilateral additivity check
Reserve sensitivity	0.5× baseline/X − 50; 2× baseline/X − 50	Within-configuration sensitivity to all reserve optimal-force values

Internal consistency, sensitivity and modeling-quality context

The five bilateral global-X conditions were described with a through-origin linear slope, conventional R^2, residuals and a descriptive quadratic term. Opposite-sign symmetry was summarized as $SI = |\Delta+ + \Delta-| / (|\Delta+| + |\Delta-|)$. The unilateral additivity index was $|\Delta left + \Delta right - \Delta bilateral| / |\Delta bilateral|$. These deterministic checks quantify implementation consistency; their R^2 and indices are not inferential measures of precision or external validity.

Reserve scaling was assessed within each configuration, using slope ratios relative to default and a prespecified practical robustness convention of 0.90–1.10. Model residual forces and moments were compared with contextual reference thresholds of 5% of external force and 1% of center-of-mass height times external force, respectively (Hicks et al. 2015). Threshold exceedance was documented, not used to discard runs. A moment-arm order-of-magnitude assessment used 96 eligible extensor fibers at t*. Axis-projection exercises were secondary, dependent on the model geometry and not anatomical measurements of disc/endplate orientation.

Results

Run verification and bilateral dose response

Three independent baseline repetitions were byte-identical in the study environment. The baseline reproduced the distributed example to within 3.015×10^{-5} stored output units under the documented combined numerical tolerance. All 14 conditions passed input identity, row-count, terminal time, finite-value and time-grid checks. The model mass was 80.6118 kg excluding the box, corresponding to a baseline L5–S1 resultant peak of 5,643.59 N (7.14 body weights); this value is model/output context rather than a validated anatomical tissue load.

At 2.0483 s, bilateral X − 50 and X + 50 mm changed the peak by + 88.38 and − 88.39 N; X − 100 and X + 100 mm changed it by + 176.79 and − 177.11 N (Table 2; Fig. 2A). The five-point slope was − 1,769.13 N/m (descriptive $R^2 = 0.999999$), with a descriptive quadratic coefficient of − 18.38 N/m². Ratios of the ± 100-mm to twice the corresponding ± 50-mm effects were 1.0002 and 1.0019; opposite-sign symmetry indices were 4.3×10^{-5} and 9.2×10^{-4}. The peak time did not shift among these modeled conditions.

Table 2
Primary modeled L5–S1 resultant peak outcomes; all maxima occurred at 2.04831146 s

Condition	Translation	Δ peak |F| (N)	Peak |F| (N)	Comment
Baseline	0	0.00	5643.59	Reference
X − 50	Bilateral global X	+ 88.38	5731.97	+ 1.57%
X + 50	Bilateral global X	−88.39	5555.21	−1.57%
X − 100	Bilateral global X	+ 176.79	5820.38	Dose extension
X + 100	Bilateral global X	−177.11	5466.48	Dose extension
Z − 50	Bilateral global Z	−2.30	5641.29	Direction check
Z + 50	Bilateral global Z	+ 2.72	5646.31	Direction check
Pelvis + 50	Pelvis local anterior axis	+ 87.97	5731.56	One-sided
Left X − 50	Left hand	+ 44.08	5687.68	Unilateral
Right X − 50	Right hand	+ 44.29	5687.89	Unilateral

Directional, pelvis-axis and unilateral checks

Z − 50 and Z + 50 mm changed the peak by − 2.30 and + 2.72 N, respectively; both exceeded the predeclared magnitude expectation of less than 1 N, and the Z symmetry index was 0.082. This check therefore only partially supported the original expectation. The one-sided pelvis local-anterior + 50-mm condition changed the peak by + 87.97 N, 0.19% below its committed prediction and 0.9945 of the

absolute global-X secant slope. Left and right unilateral X − 50 mm effects were + 44.08 and + 44.29 N; their sum reproduced the bilateral change with additivity index 5.90×10^{-5}. Positive unilateral offsets and the opposite pelvis-axis sign were not assessed.

Reserve scaling, residual context and geometry-dependent checks

X − 50 mm slopes were 26.84, 25.77 and 25.00 N per N·m at 0.5×, default and 2× reserve-actuator scaling, respectively. Ratios to default were 1.042 and 0.970, within the predefined 0.90–1.10 convention, although the absolute baseline peaks were scale dependent (Table 3; Fig. 3A). This indicates consistency of the particular perturbation effect across the tested settings; it does not validate the absolute baseline reaction.

Table 3
Within-configuration reserve-actuator sensitivity for the bilateral X − 50-mm perturbation

Reserve scale	Baseline peak (N)	Δ peak (N)	Slope (N/N m)	Ratio to default	FE reserve peak baseline / X − 50 (N m)
0.5×	5888.64	+ 92.07	26.84	1.042	5.54 / 5.62
1.0×	5643.59	+ 88.38	25.77	1.000	12.13 / 12.29
2.0×	5217.35	+ 85.76	25.00	0.970	23.73 / 24.00

The baseline residual-moment criterion was exceeded: ratio 2.55 on the interior grid and 3.08 on the complete grid (Fig. 3C). Imposed moments of 3.43 and 6.86 N·m represented 38% and 76% of the adopted moment reference. This substantial residual demand restricts interpretation of both the absolute reaction magnitude and the mechanism producing its change.

At t*, the 96 selected extensor-fiber moment arms ranged from 0.02294 to 0.05630 m, giving an order-of-magnitude 60.9–149.5 N range for the 3.43-N·m input, which included the simulated 88.38-N result. The force-weighted effective arm was 0.04376 m (78.38-N estimate). A time-resolved sacrum-axis projection gave peak differences of + 79.42 and − 79.42 N under X − 50 and X + 50 mm. Those projections are axis assumptions, not direct measurements of anatomical compression or shear.

Discussion

This technical communication isolates one computational assumption that is difficult to isolate experimentally: a precisely specified virtual translation of external hand wrenches, implemented as free-moment changes without changing measured motion or ground reactions. The almost proportional, opposite-sign global-X peak responses and close unilateral additivity demonstrate numerical and implementation consistency in the selected OpenSim instance. This should be read as a reproducible model-sensitivity benchmark, rather than a new mechanical finding about what happens when a person physically shifts a box or bar.

The result is consistent with the expectation that changes in external moment assumptions can propagate through model-predicted joint reactions, but the response magnitude depends on the entire force-sharing solution, muscle geometry and residual contributions. Differences in real squat techniques reflect multiple simultaneous changes; existing squat-comparison experiments cannot be reduced to this fixed-kinematics input transformation (Gullett et al. 2009; Goršič et al. 2024). The observed linear fit across only five prescribed computational offsets is a within-instance description, not evidence for a universal linear law.

The tested reserve optimal-force multipliers produced a relatively stable X − 50-mm sensitivity (+ 4.2%/ −3.0% relative to the default slope) despite substantial changes to absolute modeled peaks. A post hoc coordinate-filter change from 3 to 6 Hz changed the absolute baseline peak by + 68.75 N but yielded a two-sign X sensitivity of 25.77478 N/(N·m), 1.00032 of default. The attempted activation-exponent = 3 analysis failed repeated optimizations and produced no accepted result. These analyses do not establish robustness to different muscles or spine geometry, activation formulations, time steps, contact mechanics or models.

A read-only audit of FATLS APP2–APP5 found no additional alternative formulation suitable for a direct, unchanged-input comparison: APP2 failed the planned reproduction tolerance, APP3/APP4 lacked setup-referenced inputs, and APP5 used an incompatible reserve set. This package-completeness observation does not independently validate the biomechanical results. A key limitation is the elevated baseline residual-moment ratio (2.55 interior and 3.08 full grid), which indicates that the solver relied on residual moment beyond the chosen model-quality context. Consequently, the study cannot attribute the observed joint-reaction change uniquely to muscles or other internal structures (Hicks et al. 2015).

The moment-arm check established only numerical scale plausibility. Similarly, the model-axis projections change the apparent component decomposition without identifying anatomical endplate normals. The resultant magnitude was used as primary outcome because it is invariant to coordinate rotation for a given reaction vector, but its absolute value cannot be interpreted as a validated disc/contact force. Published spinal-loading studies using different lifting conditions and model definitions are informative context, not calibration targets for this specific 7-kg virtual perturbation (von Arx et al. 2021). Future investigations may extend this computational framework to real-world loaded squat variations, such as the Zercher squat, provided that exercise-specific kinematics, external forces, load-contact conditions, and appropriate model validation are adequately represented. The present numerical responses must not be transferred to those exercises.

Limitations

The source package contained one usable person, squat trial and model configuration. Repeated baseline execution establishes numerical repeatability in the study environment, not measurement reproducibility, external validity or generalizability. The perturbation adds a virtual free moment and does not model a displaced barbell, Zercher hold, forearm contact, modified posture, object inertia or new

muscle recruitment under physical load relocation. No claims about preferred exercise technique, disc pressure, injury risk or clinical interventions are supported.

Residual-moment demand exceeded the contextual threshold; the opposite pelvis-axis direction and positive unilateral directions were not analyzed. Some protocol amendments occurred after initial results and are recorded in the provenance archive. The data package excludes source-restricted FATLS trajectories and private trial exports; accordingly, readers need the original FATLS files under the source conditions to reproduce the complete pipeline. Additional tests spanning multiple trials, independent models, direct physical load variations and validation measurements are required before translating the numerical finding beyond this worked example.

Conclusion

For one recorded 7-kg box-squat trial, a virtual translation of bilateral hand wrenches generated a dose-proportional, directionally opposed change in modeled L5–S1 reaction resultant under fixed kinematics and ground reactions. Unilateral, pelvis-axis and reserve-scaling checks supported internal numerical consistency; elevated residual-moment demand and the single-trial design constrain biomechanical interpretation. The result is a transparent single-instance sensitivity benchmark, not evidence about physical lifting variants or lumbosacral injury.

Statements and Declarations

Funding: The author received no specific funding for this work.

Competing interests: The author declares no relevant financial or non-financial competing interests.

Ethics approval: This report is a secondary computational analysis of a publicly released de-identified example trial; it involved no new participant recruitment or measurement. The source investigation's ethics approval and consent procedures are described by the original investigators and are not independently asserted here.

Consent to participate: No new participant contact or data collection was performed for this computational analysis; original-study consent requirements remain governed by the source study.

Consent for publication: No identifiable participant image or private personal information is presented.

Author contributions: Jone Maycon Monteiro: conceptualization, methodology, analysis, software, validation checks, visualization, investigation, original manuscript, review and editing.

Data availability: The author-reported public reproducibility package contains scripts, aggregate results, visualizations and manifests: https://doi.org/10.5281/zenodo.23546196. Analysis-plan amendments and provenance are reported at https://doi.org/10.5281/zenodo.23560787. Original FATLS inputs, derived trajectories and private trial-level outputs are not redistributed and must be obtained from their

original source under applicable terms. Repository accessibility and licence conditions require author confirmation before submission.

Use of AI-assisted tools: OpenAI ChatGPT was used to assist with English-language editing and preparation of figures from the numerical summaries reported in this manuscript. The author remains responsible for checking all wording, numerical values, visual representations and citations. No new simulation outputs or participant data were generated by this tool.

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Figures

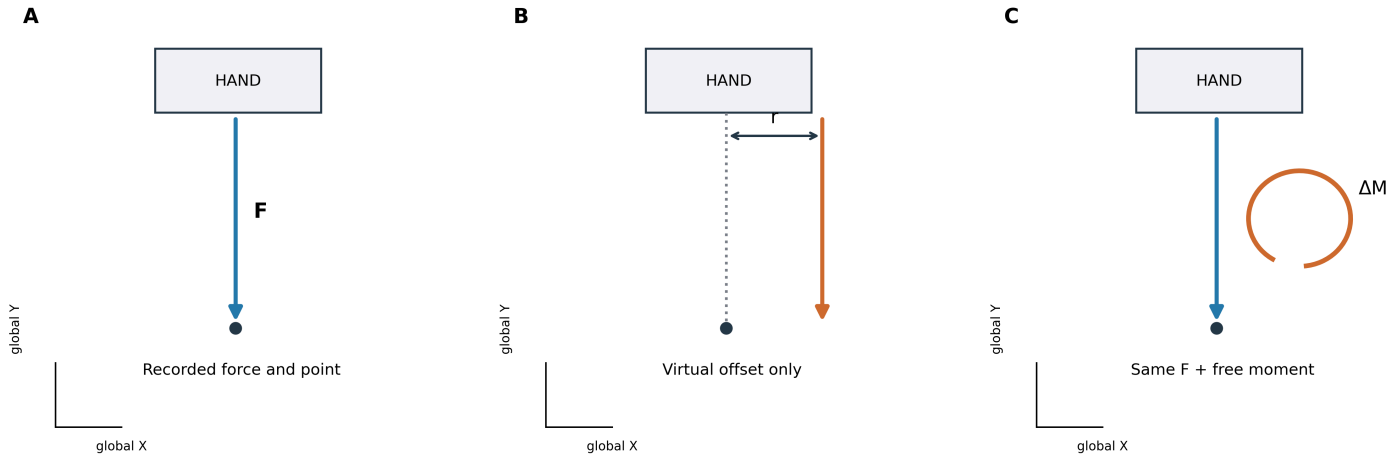


Figure 1

Controlled virtual hand-wrench perturbation. (A) Baseline measured hand force and application point. (B) Conceptual line-of-action offset r. (C) Equivalent representation applied in the model: original force and point plus free moment ΔM = r × F. This is a computational input transformation, not physical load relocation

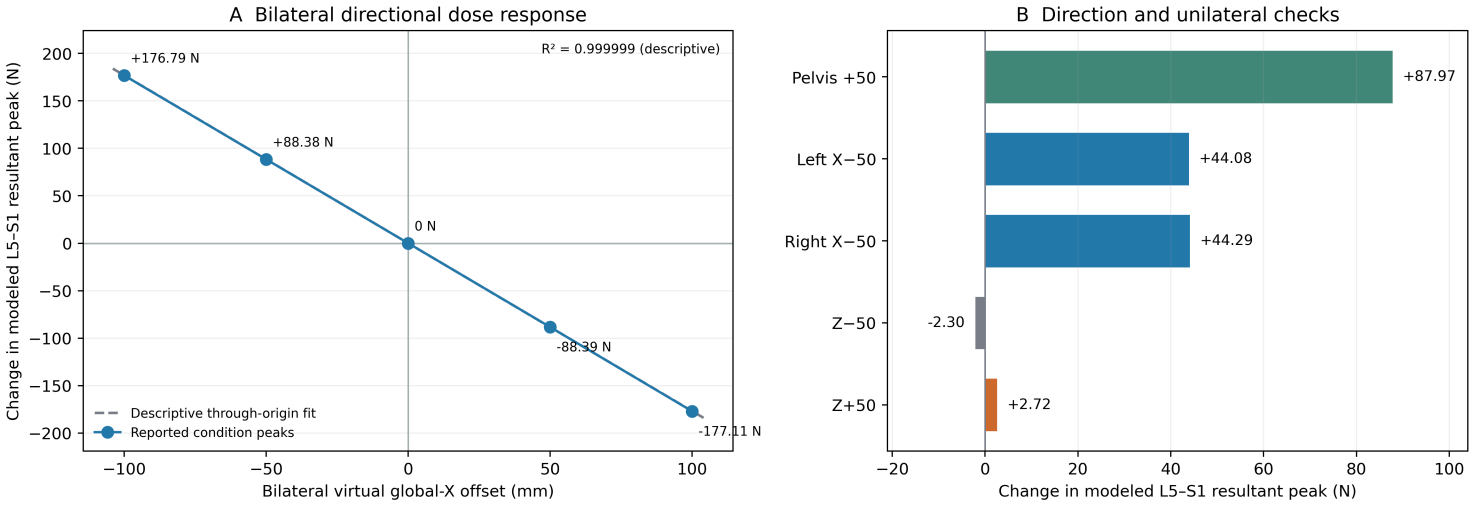


Figure 2

Directional sensitivity of the modeled L5–S1 resultant peak. (A) Five bilateral global-X conditions (single model/trial) with descriptive through-origin line. (B) Pelvis-axis, one-hand X and global-Z checks. Numerical values are derived solely from the reported accepted-condition peak summaries; no additional simulations are represented

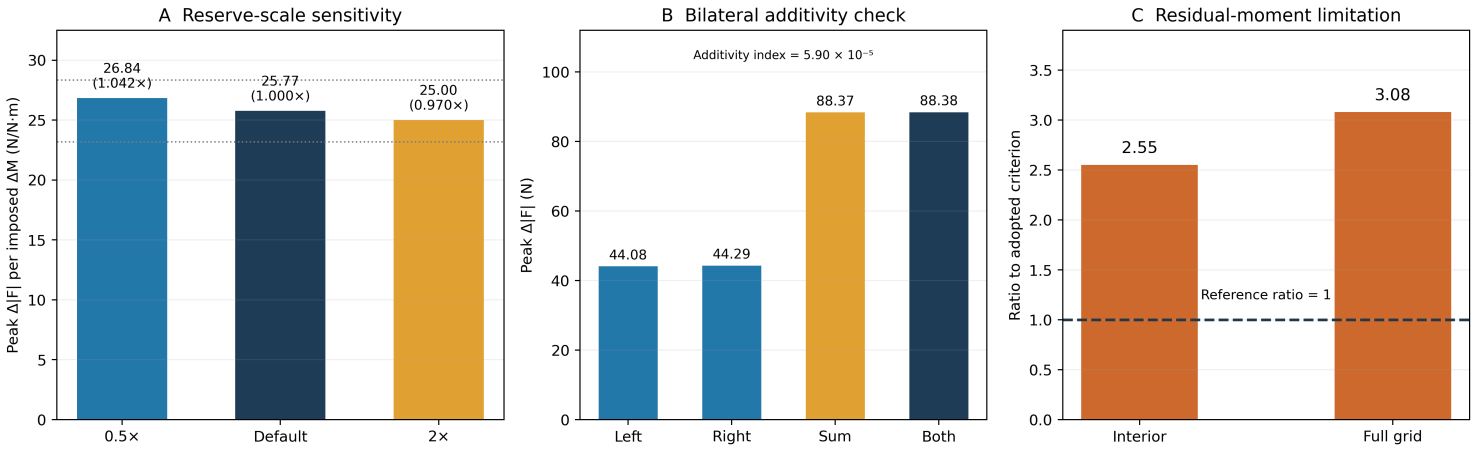


Figure 3

Internal consistency and principal quality limitation. (A) Response per unit imposed moment under reserve-actuator scaling; dotted lines mark 0.90–1.10 of the default slope. (B) Unilateral additivity (left + right compared with bilateral X−50 mm). (C) Baseline residual-moment ratios compared with the adopted contextual reference value of one. Descriptive solver-model quantities, not tissue-force validation