

PATELLAR-TENDON TRANSFORMATION UNDER CHANGING MUSCLE FORCE

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ABSTRACT

To distinguish the effects of increasing muscle force and changing patellar-tendon mechanical response on tendon strain. In this article human muscle-tendon mechanics were examined for loading exposure, tendon geometry, force-range selection, adaptation timing and measurement reliability. Axial mechanics, an exponential force-strain relation and a common-shape adaptation function were evaluated analytically. Secant rigidity obeys $Q_s = F/\epsilon$; its change therefore describes the force-strain relationship rather than independently establishing tissue adaptation. For $F : 2000 \rightarrow 2600$ N, $C : 1000 \rightarrow 1200$ N and $\beta = 20$, the calculated strain rises from 5.493% to 5.763%, a relative increase of 4.92%. Evaluating each force on both response curves separates the positive force contribution from the negative curve contribution. In a linear response, force and secant-rigidity ratios of 1.30 and 1.20 instead give an 8.33% strain increase. Equal eventual force and rigidity gains produce a temporary strain elevation when their common adaptation function advances faster for force. With 30% eventual gains and a threefold rigidity-to-force adaptation-time ratio, peak elevations are 10.63% for $g(v) = 1 - e^{-v}$ and 19.39% for $g(v) = 1 - e^{-v^2}$. Patellar-tendon transformation requires comparison of response curves at matched forces. Strain at the operating force is a separate deformation outcome. Reference preload, slope interval, anatomical segment and covariance among measurements determine whether the two comparisons can be interpreted consistently.

Keywords: patellar tendon; transformation processes; axial rigidity; load matching; nonlinear mechanics; adaptation timing; measurement uncertainty.

INTRODUCTION

Quadriceps force and patellar-tendon stiffness need not increase in the same proportion during training. Their relative changes determine the strain at the force transmitted through the tendon. Arampatzis, Mersmann and Bohm linked unequal muscle-tendon adaptation to elevated operating strain and described individualized patellar-tendon assessment (Arampatzis et al., 2020). A longitudinal force-elongation comparison must therefore distinguish movement along a response curve from a change in the curve itself.

Loading intensity, contraction duration and anatomical boundaries affect the interpretation of stiffness. Malliaras and colleagues compared contraction modes and loading intensities using specified torque intervals (Malliaras et al., 2013). In Massey's 12-week investigation, explosive and sustained contractions increased free-patellar-tendon stiffness by 20% and 16%, respectively, whereas tendon-aponeurosis stiffness increased only with sustained contractions (Massey et al., 2018). Free-tendon elongation and tendon-aponeurosis elongation consequently require separate measurements.

Patellar-tendon transformation denotes a change in the geometry or force-elongation response of the same anatomical segment between assessments. Longitudinal adolescent measurements connect cross-sectional growth with mechanical adaptation (Mersmann et al., 2017). Eriksen and colleagues found changes in older adults' patellar-tendon mechanics without detectable changes in the tendon-core collagen characteristics they measured (Eriksen et al., 2019). Radiocarbon measurements indicate limited renewal of the adult Achilles core (Heinemeier et al., 2013); this anatomical finding cannot determine patellar-tendon turnover. Cross-sectional area, estimated modulus and collagen composition are therefore distinct outcomes.

Two mechanical questions follow. First, how much of the change in operating strain accompanies a force increase, and how much accompanies a different tendon response? Second, can strain rise during training even when force and rigidity ultimately increase by equal proportions? The analysis resolves the first question by evaluating both forces on both curves and the second by deriving the existence, timing and magnitude of an interior strain extremum.

METHODS

AXIAL MECHANICS AND CALCULATION

The mechanical representation is one-dimensional and quasi-static. Tendon force is axial, cross-sectional area is represented by a segment average, and the same anatomical landmarks and joint configuration define gauge length at both assessments. Regional strain gradients, hysteresis, transverse deformation and changing load sharing are excluded. Each calculation uses positive forces, dimensions and constitutive parameters. Adaptation functions describe log changes and are not fitted to human observations.

Closed-form expressions were evaluated in double precision. Bounded numerical optimization checked the stationary maxima, and direct substitution checked the sum of the force and curve contributions against the total log-strain change. The functions in Eqs. (Exponential force-strain response) and (Sensitivity to adaptation time and curve shape) generate Figures Force-strain curves from Eq. (Exponential force-strain response) for $C_0 = 1000$ N (solid) and $C_1 = 1200$ N (dashed), with $\beta = 20$. Horizontal lines identify the 2.0- and 2.6-kN operating forces. Their four intersections give the strains in Table Strains calculated with Eq. (Exponential force-strain response) at $F_0 = 2000$ N and $F_1 = 2600$ N, with $C_0 = 1000$ N, $C_1 = 1200$ N and $\beta_0 = \beta_1 = 20$; evaluating a common force isolates the curve difference and Maximum strain elevation for equal 30% force and rigidity gains, calculated with Eq. (Sensitivity to adaptation time and curve shape). Filled points use $g(v) = 1 - e^{-v}$; open points use $g(v) = 1 - e^{-v^2}$. Each horizontal segment joins the two peak values at one adaptation-time ratio. At $\rho = 3$, the elevations are 10.63% and 19.39%; at $\rho = 1$, both are zero. Calculation and plotting code follows the document body in the LaTeX file.

REFERENCE CONDITIONS AND MECHANICAL QUANTITIES

Let F be tendon force (N), A cross-sectional area (mm^2), L reference gauge length (mm), and ΔL elongation (mm) from that reference. Engineering stress and strain are

$$\sigma = \frac{F}{A}, \quad \epsilon = \frac{\Delta L}{L}. \quad (1)$$

The origin must be specified. A measured "resting" length is not automatically a stress-free length. If a fixed reference preload $F_r > 0$ is used, define $P = F - F_r$ and $\epsilon_r = [\ell(F) - \ell(F_r)]/\ell(F_r)$. The reference-relative secant is $P/[\ell(F) - \ell(F_r)]$; it must not be mixed with the absolute-force secant below. Reference-relative quantities answer an incremental-deformation question and omit any unmeasured prestrain. All subsequent examples adopt an idealized zero-force, zero-elongation origin.

At a nonzero operating point, define secant stiffness, secant modulus and secant axial rigidity by

$$K_s = \frac{F}{\Delta L}, \quad E_s = \frac{\sigma}{\epsilon}, \quad Q_s = E_s A = K_s L = \frac{F}{\epsilon}. \quad (2)$$

Their units are N/mm, N/mm² and N, respectively. By contrast, tangent stiffness is a derivative:

$$K_t = \frac{dF}{d\Delta L} = \frac{A}{L} E_t, \quad E_t = \frac{d\sigma}{d\epsilon}. \quad (3)$$

These relations assume fixed A and L while a curve is evaluated. A fitted slope across a finite high-force interval is an interval estimate, not necessarily a secant from the origin. For an affine high-force approximation $\Delta L = c_0 + F/K_t$, total strain is $(c_0 + F/K_t)/L$; deleting the intercept removes part of the elongation.

For two assessments, denote positive ratios by $R_X = X_1/X_0$. Eq. (Reference conditions and mechanical quantities) gives

$$R_\epsilon = \frac{R_F}{R_{E_s} R_A} = \frac{R_F}{R_{K_s} R_L} = \frac{R_F}{R_{Q_s}}, \quad m = \ln R_\epsilon. \quad (4)$$

Strain decreases if and only if $R_{Q_s} > R_F$. For a linear force-strain response with $R_F = 1.30$ and $R_{Q_s} = 1.20$, $R_\epsilon = 1.08333$. Setting $\epsilon_0 = 6\%$ gives $\epsilon_1 = 6.5\%$, an increase of 0.5 percentage points. Eq. (Reference conditions and mechanical quantities) requires secant rigidity at the specified operating points; tangent stiffness cannot be substituted for K_s .

Eq. (Reference conditions and mechanical quantities) is descriptive: Q_s is computed from F and ϵ , so the ratio is not an independent test of a biological cause. In a nonlinear tendon, Q_s changes when the operating point changes even if the response curve is invariant. Independent interpretation therefore requires comparison of the response functions themselves within a common load domain.

NONLINEAR SEPARATION OF FORCE AND CURVE CHANGES

EXPONENTIAL FORCE-STRAIN RESPONSE

Define the exponential material relation

$$\sigma = S\{\exp(\beta\epsilon) - 1\}, \quad C = AS, \quad \phi(F; C, \beta) = \frac{\ln(1 + F/C)}{\beta}, \quad (5)$$

where $S > 0$ has stress units, $C > 0$ has force units and $\beta > 0$ is dimensionless. The strain response is $\epsilon = \phi(F; C, \beta)$, with

$$K_t(F) = \frac{\beta(F + C)}{L}. \quad (6)$$

For $C = 1000$ N, $\beta = 20$ and $L = 50$ mm, moving from 2 to 3 kN raises tangent stiffness from 1200 to 1600 N/mm, an increase of 33.33%. The strains are 5.493% and 6.931%. No constitutive parameter has changed: the measurement samples a steeper part of the same curve.

This dependence is explicit in the local log sensitivity. With $x = F/C$,

$$d \ln \epsilon = h(x)\{d \ln F - d \ln A - d \ln S\} - d \ln \beta, \quad h(x) = \frac{x}{(1+x)\ln(1+x)}. \quad (7)$$

Here $0 < h(x) < 1$ for $x > 0$, and $h(x) \rightarrow 1$ as $x \rightarrow 0$. The linear sensitivity is the small- x limit of Eq. (Exponential force-strain response). Because $C = AS$, an area measurement is necessary to distinguish changes in A from changes in the stress-scale parameter S .

CROSS-EVALUATION AND SYMMETRIC ALLOCATION

Let θ_j denote the curve parameters at visit j , and define four positive strain values $\epsilon_{ij} = \phi(F_i; \theta_j)$. Both forces must lie inside the domain measured at both visits; otherwise cross-evaluation relies on extrapolation. The first subscript identifies force, the second the response curve. A symmetric allocation averages the two possible orders of changing force and curve:

$$D_F = \frac{1}{2} \left\{ \ln \frac{\epsilon_{10}}{\epsilon_{00}} + \ln \frac{\epsilon_{11}}{\epsilon_{01}} \right\}, \quad (8)$$

$$D_T = \frac{1}{2} \left\{ \ln \frac{\epsilon_{01}}{\epsilon_{00}} + \ln \frac{\epsilon_{11}}{\epsilon_{10}} \right\}, \quad (9)$$

$$D_F + D_T = \ln \frac{\epsilon_{11}}{\epsilon_{00}}. \quad (10)$$

It avoids choosing one comparison order, but it is an allocation convention rather than a unique biological partition. The curve contribution includes all differences encoded by θ , including geometry or measurement-state differences. Experimental control and independently justified parameter estimation are still required for causal interpretation.

TABLE 1. STRAINS CALCULATED WITH EQ. (Exponential force-strain response) AT $F_0 = 2000$ N AND $F_1 = 2600$ N, WITH $C_0 = 1000$ N, $C_1 = 1200$ N AND $\beta_0 = \beta_1 = 20$.

Force condition	Curve 0 strain (%)	Curve 1 strain (%)
$F_0 = 2000$ N	$\epsilon_{00} = 5.49306$	$\epsilon_{01} = 4.90415$
$F_1 = 2600$ N	$\epsilon_{10} = 6.40467$	$\epsilon_{11} = 5.76340$

For Table Strains calculated with Eq. (Exponential force-strain response) at $F_0 = 2000$ N and $F_1 = 2600$ N, with $C_0 = 1000$ N, $C_1 = 1200$ N and $\beta_0 = \beta_1 = 20$, $D_F = 0.157494$ and $D_T = -0.109452$. The corresponding multiplicative contributions are $\exp(D_F) = 1.17057$ and $\exp(D_T) = 0.896325$; their product is the total strain ratio 1.049214. Force elevation increases strain, curve change decreases it, and their combined effect is a 4.92% increase. The result differs from 8.33% because a 20% change in C is not a 20% change in operating secant rigidity. Figure Force-strain curves from Eq. (Exponential force-strain response) for $C_0 = 1000$ N (solid) and $C_1 = 1200$ N (dashed), with $\beta = 20$. Horizontal lines identify the 2.0- and 2.6-kN operating forces. Their four intersections give the strains in Table Strains calculated

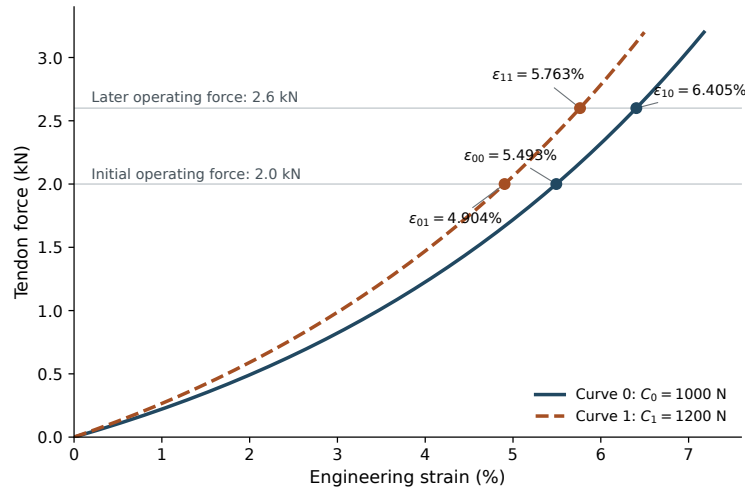


FIGURE 1. FORCE-STRAIN CURVES FROM EQ. (Exponential force-strain response) FOR $C_0 = 1000$ N (SOLID) AND $C_1 = 1200$ N (DASHED), WITH $\beta = 20$. HORIZONTAL LINES IDENTIFY THE 2.0- AND 2.6-KN OPERATING FORCES. THEIR FOUR INTERSECTIONS GIVE THE STRAINS IN TABLE Strains calculated with Eq. (Exponential force-strain response) at $F_0 = 2000$ N and $F_1 = 2600$ N, with $C_0 = 1000$ N, $C_1 = 1200$ N and $\beta_0 = \beta_1 = 20$; EVALUATING A COMMON FORCE ISOLATES THE CURVE DIFFERENCE.

with Eq. (Exponential force-strain response) at $F_0 = 2000$ N and $F_1 = 2600$ N, with $C_0 = 1000$ N, $C_1 = 1200$ N and $\beta_0 = \beta_1 = 20$; evaluating a common force isolates the curve difference displays the four evaluations directly.

Matched force and matched stress address different comparisons when area changes. The former assesses structural response to a given transmitted force; the latter assesses the estimated material response to a given nominal stress. For either comparison, slope intervals, rate, reference state and geometry must be specified. Changes in fitted C and β may also be poorly distinguishable over a narrow force range; fitting a curve does not guarantee identifiable material parameters.

ADAPTATION TIMING AND TRANSIENT STRAIN ELEVATION

A GENERAL COMMON-SHAPE RESULT

To isolate timing, assume a load-independent linear relation, constant L , and positive eventual log gains $a = \ln G_F$ and $b = \ln G_Q$. Let g be continuous, strictly increasing, $g(0) = 0$ and $g(\infty) = 1$. Define

$$\ln \frac{F(t)}{F(0)} = a g(t/\tau_F), \quad \ln \frac{Q(t)}{Q(0)} = b g(t/\tau_Q), \quad \tau_F, \tau_Q > 0. \quad (11)$$

Then $m(t) = a g(t/\tau_F) - b g(t/\tau_Q)$. If $a = b > 0$ and $\tau_Q > \tau_F$, monotonicity gives $m(t) > 0$ at every finite $t > 0$, while $m(0) = 0$ and $m(\infty) = 0$. A positive interior maximum therefore exists. The qualitative result requires neither an exponential shape nor a particular calendar duration. It does require a common adaptation shape and onset; different response functions or delayed onsets need their own analysis.

STATIONARY-POINT CONDITIONS FOR A SPECIFIED FAMILY

For explicit magnitude and timing, choose

$$g_n(v) = 1 - \exp(-v^n), \quad n \geq 1, \quad u = t/\tau_F, \quad \rho = \tau_Q/\tau_F. \quad (12)$$

The exponential approach has $n = 1$; the $n = 2$ approach has an initial accelerating phase and then decelerates. In either case, τ is the time to 63.2% of the eventual log gain. Equal n is assumed for force and rigidity. Hence

$$m(u) = a(1 - e^{-u^n}) - b(1 - e^{-(u/\rho)^n}). \quad (13)$$

For $a, b > 0$ and $\rho \neq 1$, an interior stationary point exists precisely when

$$w_* := \frac{\ln(a\rho^n/b)}{1 - \rho^{-n}} > 0, \quad u_* = w_*^{1/n}. \quad (14)$$

Its type follows from the second derivative, not from positivity alone. If $\rho > 1$, the stationary point is a maximum and exists when $a\rho^n > b$. If $\rho < 1$, it is a minimum and exists when $a\rho^n < b$. When $\rho = 1$, $m(u) = (a - b)(1 - e^{-u^n})$ is

monotone unless $a = b$, when it is identically zero. Zero force gain gives a monotone decline; zero rigidity gain gives a monotone rise. These boundary cases are evaluated directly rather than inserted into a logarithm involving zero.

For $n = 1$, the maximum condition is the initial-rate inequality $a/\tau_F > b/\tau_Q$. For $n > 1$, both initial derivatives are zero; the relevant inequality compares the leading terms a/τ_F^n and b/τ_Q^n . The eventual ratio is always $\exp(a - b) = G_F/G_Q$. A strain peak can therefore precede an eventual reduction.

TABLE 2. INTERIOR STRAIN EXTREMA AND EVENTUAL STRAIN RATIOS FROM EQ. (Stationary-point conditions for a specified family) WITH $n = 1$. G_F AND G_Q ARE THE SPECIFIED EVENTUAL GAINS; $\rho = \tau_Q/\tau_F$ AND $u = t/\tau_F$.

G_F	G_Q	ρ	Interior event	Ratio at event	Eventual ratio
1.15	1.30	3.0	Maximum, $u = 0.70323$	1.01588	0.88462
1.30	1.30	3.0	Maximum, $u = 1.64792$	1.10626	1.00000
1.50	1.30	3.0	Maximum, $u = 2.30087$	1.25149	1.15385
1.15	1.30	1.5	Monotone decline	No interior value	0.88462
1.30	1.30	0.5	Minimum, $u = 0.69315$	0.93651	1.00000

SENSITIVITY TO ADAPTATION TIME AND CURVE SHAPE

With equal gains $a = b = \ln G$ and $\rho > 1$, substitution into Eq. (Stationary-point conditions for a specified family) gives

$$\frac{\epsilon(u_*)}{\epsilon(0)} = \exp \left[\ln G (1 - \rho^{-n}) \rho^{-n/(\rho^n - 1)} \right]. \quad (15)$$

The peak tends to one as $\rho \rightarrow 1$ and tends to G as $\rho \rightarrow \infty$. Its magnitude increases with G ; slower relative rigidity adaptation also increases the peak within this family. Figure Maximum strain elevation for equal 30% force and rigidity gains, calculated with Eq. (Sensitivity to adaptation time and curve shape). Filled points use $g(v) = 1 - e^{-v}$; open points use $g(v) = 1 - e^{-v^2}$. Each horizontal segment joins the two peak values at one adaptation-time ratio. At $\rho = 3$, the elevations are 10.63% and 19.39%; at $\rho = 1$, both are zero compares $n = 1$ and $n = 2$ for $G = 1.30$. At $\rho = 3$, the maxima are 1.10626 and 1.19387, attained at $u = 1.64792$ and $u = 1.57222$. Both functions produce a transient elevation, but the $n = 2$ peak exceeds the $n = 1$ peak by 8.76 percentage points. The difference arises solely from adaptation shape.

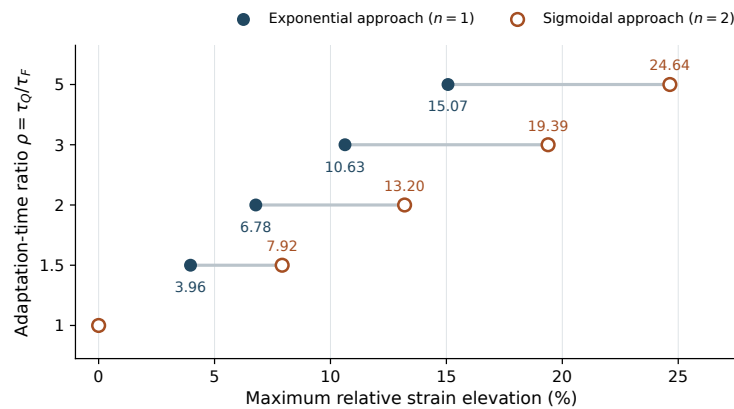


FIGURE 2. MAXIMUM STRAIN ELEVATION FOR EQUAL 30% FORCE AND RIGIDITY GAINS, CALCULATED WITH EQ. (Sensitivity to adaptation time and curve shape). FILLED POINTS USE $g(v) = 1 - e^{-v}$; OPEN POINTS USE $g(v) = 1 - e^{-v^2}$. EACH HORIZONTAL SEGMENT JOINS THE TWO PEAK VALUES AT ONE ADAPTATION-TIME RATIO. AT $\rho = 3$, THE ELEVATIONS ARE 10.63% AND 19.39%; AT $\rho = 1$, BOTH ARE ZERO.

The time analysis and the nonlinear curve analysis isolate different questions. Eq. (A general common-shape result) assumes independently specified linear rigidity. Applying its numerical peak to a nonlinear tendon would require modelling the evolution of the constitutive parameters and operating force together. Likewise, a participant-average trajectory cannot establish that every participant has the same time ordering.

MEASUREMENT COVARIANCE AND UNCERTAINTY

Let $z_F = \ln R_F$, $z_K = \ln R_{K_s}$ and $z_L = \ln R_L$, so that $m = z_F - z_K - z_L$. With covariance matrix Σ and coefficient vector $c = (1, -1, -1)^T$,

$$\text{Var}(m) = c^T \Sigma c = V_F + V_K + V_L - 2C_{FK} - 2C_{FL} + 2C_{KL}. \quad (16)$$

The variables are paired log ratios, so each variance already includes uncertainty from both visits. Covariances are needed when force, elongation, length and derived stiffness share recordings. If modulus is calculated as $K_s L/A$, then multiplication by the same A cancels area exactly; treating the derived modulus and area as independent measurements introduces spurious uncertainty. Resampling complete paired trials preserves this dependency more naturally than resampling derived quantities separately.

With fixed L , Eq. (Measurement covariance and uncertainty) reduces to

$$\text{Var}(m) = s_F^2 + s_K^2 - 2\gamma_{FK} s_F s_K, \quad (17)$$

where s_F and s_K are the standard deviations of the paired log-force and log-stiffness ratios, and γ_{FK} is their correlation. Positive correlation reduces the variance of their difference; negative correlation increases it. A strain interval therefore requires the paired measurement covariance, not merely separate errors for force and stiffness.

Direct strain, obtained from tracked elongation and reference length, is therefore the primary deformation outcome. Its decomposition into force and rigidity explains the mechanics but provides no independent corroboration. Curve fitting and cross-evaluation should also propagate uncertainty in curve parameters, force estimates and their shared measurements.

INTERPRETATION OF PATELLAR-TENDON MEASUREMENTS

COMMON FORCE AND OPERATING FORCE

Common-force comparisons and operating-force comparisons answer different questions. The 70–80% initial maximal-torque interval in Massey's investigation holds the absolute evaluation range constant (Massey et al., 2018). Quinlan's final 10% of maximal force instead follows the maximum attained at each visit (Quinlan et al., 2021). A stiffness change over the latter interval can include movement to a different part of a nonlinear curve. Strain at maximum voluntary force describes deformation at that contraction intensity; it does not specify strain during jumping or running.

A patellar-tendon comparison requires the same patellar and tibial landmarks, joint angle, reference preload, loading rate and preconditioning. Tendon-force estimation additionally requires the patellar moment arm and treatment of antagonist and gravitational moments. Ultrasound and dynamometer synchronization determines which elongation belongs to each force. If one visit does not reach the intended comparison force, the matched-load interval ends at the highest force observed at every visit.

Schulze and colleagues demonstrated that averaging multiple trials affects the reliability of in vivo patellar-tendon elongation (Schulze et al., 2012). Trial count and within-visit repeatability therefore belong alongside the elongation estimate. Equal ramp durations do not ensure equal loading rates when the attained force increases: the force-time trajectory must be examined together with the force-elongation curve.

BIOLOGICAL AND CLINICAL INTERPRETATION

At a fixed force, a slope change describes structural mechanical adaptation over the specified interval. Cross-sectional area describes geometry; stress-normalized slope describes the estimated material response. Eriksen's simultaneous mechanical measurements and tendon-core biopsies show why these outcomes cannot substitute for collagen measurements (Eriksen et al., 2019).

Higher pre-symptom patellar-tendon strain was associated with later clinically relevant tendon pain in adolescent athletes (Mersmann et al., 2023). In a separate adolescent handball intervention, tendon-pain prevalence decreased without a significant reduction in maximum strain (Mersmann et al., 2021). Absolute strain, relative strain change and pain prevalence must consequently remain separate outcomes. Neither m nor the calculated timing peak has been validated as a pain predictor.

RESOLVING THE ADAPTATION TIME COURSE

An initial-to-final ratio cannot identify G_F , G_Q , τ_F and τ_Q separately. Intermediate measurements are needed to locate an interior extremum and distinguish early change from a plateau. Quinlan's two-week assessment spacing and Bontemps's weeks-zero, -two and -four measurements illustrate two actual sampling schedules (Quinlan et al., 2021; Bontemps et al., 2024); neither schedule determines a universal adaptation time. Estimation of Eq. (Stationary-point conditions for a specified family) requires paired force and strain observations, a consistent anatomical segment and a common force interval at each visit. Different onsets or different shape parameters require separate force and rigidity functions.

CONCLUSION

Patellar-tendon transformation requires evaluation of the same anatomical segment over the same force interval. In the specified exponential calculation, a 30% force increase and a 20% force-scale increase raise strain by 4.92%; the two changes act in opposite directions. Equal eventual force and rigidity gains also permit a temporary strain maximum when rigidity adapts more slowly. Its magnitude depends on adaptation shape. Matched-force response curves, strain at the operating force, a fixed reference state and paired measurement covariance are therefore necessary to distinguish structural adaptation from altered loading.

DECLARATIONS

CONFLICT OF INTEREST

The author declares that there are no conflicts of interest related to this study.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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