ARL-TN-1299 ● FEB 2026

User Documentation for a Skeletal Muscle Constitutive Model

by John D. Clayton

NOTICES

Disclaimers

ARL-TN-1299 ● FEB 2026

User Documentation for a Skeletal Muscle Constitutive Model

John D. Clayton
DEVCOM Army Research Laboratory

REPORT DOCUMENTATION PAGE

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED	
		START DATE	END DATE
February 2026	Technical Note	01 Aug 2025	31 Jan 2026

4. TITLE AND SUBTITLE
User Documentation for a Skeletal Muscle Constitutive Model

5a. CONTRACT NUMBER	5b. GRANT NUMBER	5c. PROGRAM ELEMENT NUMBER
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
John D. Clayton

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
DEVCOM Army Research Laboratory ATTN: FCDD-RLA-TB Aberdeen Proving Ground, MD 21005-5066	ARL-TN-1299

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES
ORCID: John D. Clayton, 0000-0003-4107-6282

14. ABSTRACT
This technical note provides user documentation for a constitutive model of skeletal muscle implemented as a user-material subroutine in the LS-DYNA software. Pseudocode explaining the computational workflow is supplied. History variables, material parameters, and user-specified controls are identified. Syntax for the material model block in the LS-DYNA input file is explained. A sample input file for deformation of a single hexahedral element is provided with recommended values of parameters.

15. SUBJECT TERMS
Skeletal Muscle, Continuum Mechanics, Mixture Theory, Injury Biomechanics, LS-DYNA, Terminal Effects

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
a. REPORT	b. ABSTRACT	C. THIS PAGE		
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UU	27

19a. NAME OF RESPONSIBLE PERSON	19b. PHONE NUMBER *(Include area code)*
John D. Clayton <john.d.clayton1.civ@army.mil>	(520) 691-5636

STANDARD FORM 298 (REV. 5/2020)
Prescribed by ANSI Std. Z39.18

Contents

Acknowledgments

I would like to acknowledge support of ARL's Terminal Effects Competency. I thank Dr. Carolyn Hampton for assistance with use of Department of Defense High Performance Computing systems. Dr. Hampton is also thanked for collaboration and co-authorship on the original journal article[1] describing the underlying theoretical-computational model.

[1]Clayton J, Hampton C. Dynamic damage in active and passive skeletal muscle: a continuum mechanical model. International Journal of Engineering Science. 2026;221:104472.

1. Introduction

This technical note provides user documentation for a constitutive model of skeletal muscle[1] implemented for 3-D finite element (FE) simulations as a user-material subroutine in the LS-DYNA software.[2] Potential users should also consult the LS-DYNA software manuals, currently available at https://lsdyna.ansys.com/manuals/, for instructions on how to compile and execute generic user-material subroutines in `LS-DYNA`. This note is of similar structure to a recent manual[3] of a constitutive model for liver likewise implemented in `LS-DYNA`. User documentation for a constitutive model of lung tissue mechanics and injury,[4,5] also implemented in LS-DYNA, was provided in previous technical reports.[6,7]

The muscle constitutive model is implemented in the `FORTRAN` programming language as a user-defined material in the `LS-DYNA` software, identified by user-defined material number 48. The global subroutine for the constitutive update is named `umat48`. This file, in turn, is inserted in the master file `dyn21umats.f` and recompiled with the source prior to execution, as explained in the `LS-DYNA` documentation.[2] Aforementioned implementations for liver[3,8] and lung[6,7] are assigned respective user-material numbers of 49 and 50, with corresponding subroutines `umat49` for liver and `umat50` for lung in the master file `dyn21umats.f`.

The present implementation is limited to explicit dynamics calculations. As such, no tangent stiffness tensor that would be needed for implicit calculations is required. Per standard conventions of the software, in each time increment $t \rightarrow t + \Delta t$, the local deformation gradient $\boldsymbol{F}$ is supplied at the end of the time step, as are values of deformation rate $\boldsymbol{d}$, material properties, and state variables at the beginning of the step. The user-material subroutine calculates, at each integration point, the Cauchy stress tensor $\boldsymbol{\sigma}$ and the state variables at the end of the time step, including temperature θ. To date, only isothermal and adiabatic simulations (i.e., no heat conduction) have been tested. The model has been verified only for `*ELEMENT_SOLID` continuum elements; shell elements are not supported.

The objective of this note is to aid transition of a skeletal muscle constitutive model to applied research on injury mechanics[9] with the `LS-DYNA` software. The reader is referred to the original journal article[1] for details on underlying theory and certain computational methods that are not reproduced in this note. Prior references on soft-tissue mechanics and injury by the author's research group culminating in the present constitutive model are openly available.[8,10–16] Software in usable `*.f` format (e.g., `dyn21umats.f`) and input files in usable `*.k` format can be provided to collaborators holding valid `LS-DYNA` licenses upon request. A stand-alone `FORTRAN` program similar to that described by Clayton and Lloyd[17] has also been implemented for verification testing of the muscle model constitutive routines. This program, not documented in the present note but available upon request, can be used in lieu of `LS-DYNA` during development and proofing stages of generic user-material model subroutines.

The present computer implementation, namely, `umat48`, includes extra features that are not described in its original application[1] to transversely isotropic skeletal muscle. Simulations in the original application presumed the tissue contains only a single muscle fiber family. The current computer implementation allows for up to two fiber families of possibly different orientations. As such, the present implementation could be used for other kinds of fibrous soft tissues, such as cardiac muscle[16,18] or skin[12,14] with a higher degree of anisotropy (e.g., orthotropy). A second extra feature is allowance of a more general time-dependent activation function for tissue stimulation. The original study[1] only considered a Heaviside unit step function distinguishing between null and full activation. The `umat48` subroutine includes time dependence via a combination of polynomial and sinusoidal terms. The original application[1] always enforced the switching function[19] that nullifies fiber contributions to stress when compressed along their axial direction. The `umat48` subroutine includes options to enable or disable the switching function, where the latter choice provides for fiber stiffness in compression. Finally, the original work[1] always included dilatational (i.e., volumetric expansive) strain energy in the driving force for matrix damage and always included total volumetric energy in the driving force for matrix and fiber injury. More generally, the current implementation provides options that can exclude dilatational energy from the damage kinetics and can exclude tensile or total volumetric energy from local injury criteria.

Basic code structure (i.e., pseudocode) and syntax for the material model block in the LS-DYNA input file are described in Section 2. History variables, parameters with recommended values, and user-specified controls for the material input cards are identified. A sample input file for uniaxial (i.e., 1-D) deformation of a single 3-D hexahedral element is provided in Section 3. Notation for acronyms and symbols supplementing the original reference[1] is listed after the bibliography of Section 4.

2. Pseudocode, Variables, and Syntax

2.1 Pseudocode

The `umat48` program for `LS-DYNA` contains 13 internal subroutines: `pressure48`, `volenergy48`, `deviator48`, `viscomatrix48`, `viscofiber48`, `degrade48`, `damage48`, `inj48`, `metric48`, `theta48`, `active48`, `det48`, and `inverse48`. The last two calculate the determinant and inverse, respectively, of a 3×3 matrix. The other 11 internal subroutines are defined implicitly in the context of pseudocode below that outlines procedures and calculations performed in `umat48` (where appropriate, Section numbers in the main journal article[1] are listed in square braces $[\,\cdot\,]$ for reference):

1. Start
2. Assign material properties supplied by user input file
3. Initialize or assign state variables from end of previous time step
4. Receive deformation gradient $\boldsymbol{F}$ at end of current step, calculate J [Section 2.1]
5. Calculate solid partial pressure using equation of state (EOS) [Section 3.1] by calling `pressure48`
6. Calculate fluid partial pressure using EOS [Section 3.1] by calling `pressure48`
7. Calculate solid deviatoric elastic stress, matrix strain energy, and fiber strain energy [Section 3.1] by calling `deviator48`, where the latter calls `degrade48` as needed for strength reductions from damage [Section 3.4]
8. Calculate Lagrangian strain increment $\dot{\boldsymbol{C}}\Delta t$ using $\boldsymbol{F}$ and $\boldsymbol{d}$ [Section 2.4]
9. Calculate matrix viscoelastic stress, free energy, and dissipation contributions for up to $m = 2$ relaxation times [Section 3.2] by calling `viscomatrix48` for each m
10. Calculate viscoelastic stress, free energy, and dissipation contributions for up to two fiber families $k = 1, 2$ having up to $n = 2$ relaxation times [Section 3.2] by calling `viscofiber48` for each k and n
11. Calculate active stress [Sections 3.3 and 4.1] for up to two fiber families $k = 1, 2$ having the same activation factor $\Delta_{\mathrm{A}}(t) \in [0, 1]$ by calling `active48`
12. Calculate determinant of non-Euclidean metric $\hat{\boldsymbol{G}}$ used in degradation model [Section 3.4] and injury model [Section 3.7] by calling `metric48`
13. Calculate volumetric thermoelastic strain energy [Section 3.1] by calling `volenergy48`

14. Add matrix deviatoric strain energy, viscoelastic energy, and volumetric energy as appropriate to obtain driving force for matrix damage [Section 3.4]
15. Calculate rate of matrix damage $\bar{D}$, its updated value not to exceed unity, and dissipation contribution [Section 3.4] by calling `damage48`
16. Add fiber deviatoric strain energy and fiber viscoelastic energy to obtain driving force for damage to fiber k [Section 3.4]
17. Calculate rate of fiber damage D_k, its updated value not to exceed unity, and dissipation contribution [Section 3.4] by calling `damage48` for each fiber family $k = 1, 2$
18. Calculate energetic driving forces (free energy sums) and updated injury measures for matrix $\bar{I}$ and fibers I_k [Section 3.7] by successively calling `inj48` for the matrix and possible fiber families $k = 1, 2$
19. Calculate the contribution of bulk viscosity to dissipation [Section 3.5]; viscous pressure $\hat{p}$ is implemented by `LS-DYNA` outside the `umat48` routine
20. If simulation is not isothermal, update temperature θ [Section 3.6] including contributions from EOS and total dissipation by calling `theta48`
21. Add pressure and deviatoric contributions to give total stress $\boldsymbol{\sigma}$ for mixture [Section 3.6] at end of step
22. Store temperature θ and other state variables as `LS-DYNA` history variables at end of step
23. Return
24. End

2.2 History Variables

The `LS-DYNA` implementation of the skeletal muscle model stores a total of 93 history variables in the `hsv` vector. These are identified as follows:

HISTORY VARIABLES

`hsv` (1)	temperature θ
`hsv` (2)	matrix damage order parameter $\bar{D}$
`hsv` (3)	fiber damage order parameter D_k ($k = 1$)
`hsv` (4)	fiber damage order parameter D_k ($k = 2$)
`hsv` (5)	matrix injury measure $\bar{I}$
`hsv` (6)	fiber injury measure I_k ($k = 1$)

`hsv` (7)	fiber injury measure I_k ($k = 2$)
`hsv` (8)	fiber active stress measure $\tilde{\sigma}_k = n^{\mathrm{S}}_{\star} P_{\mathrm{A}k}/\lambda_k$ ($k = 1$)
`hsv` (9)	fiber active stress measure $\tilde{\sigma}_k = n^{\mathrm{S}}_{\star} P_{\mathrm{A}k}/\lambda_k$ ($k = 2$)
`hsv` (10)–(12)	cumulative energy for matrix and fiber ($k = 1, 2$) viscoelasticity
`hsv` (13)–(36)	internal variables for matrix viscoelasticity
`hsv` (37)–(60)	internal variables for fiber ($k = 1$) viscoelasticity
`hsv` (61)–(84)	internal variables for fiber ($k = 2$) viscoelasticity
`hsv` (85)–(93)	components of deformation gradient $\boldsymbol{F}$

The first nine history variables, calculated in the user subroutine `umat48`, and the last nine (i.e., $\boldsymbol{F}$; see Clayton[20] or any continuum mechanics reference) supplied by the `LS-DYNA` main routine, are most often of keen interest for postprocessing. The other 75 possible variables are required by `umat48` to integrate the kinetic equations for viscoelasticity for all potential modes and relaxation times; these and complementary variables (e.g., $\{\boldsymbol{Q}, \boldsymbol{\Gamma}, \Psi\}$) are likely of low interest to the user in the context of postprocessing and results visualization.

2.3 Input File Syntax

User-specified input for the material model first comprises 48 local material constants read from the input file and stored in the `cm` vector. These are supplied in the input file block as six additional lines or "cards", with eight constants per card, that follow the first two obligatory cards for any material model. Furthermore, 24 additional material constants are stored in the `cma` vector. These 24 are supplied in the input file as 3 more cards, 8 constants per card, that immediately follow the first 48.

See the end of this technical note and Table 1 of the main journal article[1] for notation and more thorough material property definitions. Suggested values in what follows correspond primarily to rat tibialis anterior muscle.[1] In the suggested case, the fraction of occluded extracellular fluid is 10%, the tissue has a single fiber family, and both the matrix and fibers have a single viscoelastic relaxation mode. Higher values of the matrix shear modulus $\mu_{\mathrm{S}} = 4$ kPa and damage threshold $\bar{W}_{\chi}/\mu_{\mathrm{S}} = 25$ were obtained for porcine muscle.[1]

As noted in Section 1, a more general form of activation function Δ_{A} than originally prescribed[1] is enabled by the current computer implementation:

$$\tilde{\Delta}_{\rm A}(t) = d_0 + d_1(t - t_{\rm A0}) + d_2(t - t_{\rm A0})^2 + d_3 \sin(d_4 + d_5(t - t_{\rm A0})),$$
$$\Delta_{\rm A}(t) = \begin{cases} \min[\tilde{\Delta}_{\rm A}(t), 1] & \text{if } t \in [t_{\rm A0}, t_{\rm A1}] \text{ and } \tilde{\Delta}_{\rm A}(t) > 0, \\ 0 & \text{if } t < t_{\rm A0},\ t > t_{\rm A1},\ \text{or } \tilde{\Delta}_{\rm A}(t) < 0. \end{cases} \tag{1}$$

Though any consistent set of units can be used, recommended International System of Units (SI) units (not all independent) are $\{\rm kg, m, sec, N, Pa, K\}$. Any parameters in cards 3–11 labeled as "flags" should be input as floating point numbers (e.g., 0., 1., 2., 3.) rather than integers since the `cm` and `cma` arrays are hardcoded as real variables in the `LS-DYNA` source. Flags in either array are converted from real to integer in the `umat48` subroutine as appropriate. Input in `LS-DYNA` syntax (e.g., in the `*.k` file) is as follows, noting cards 4 and 5 use the same variable names for respective solid and fluid phases:

`*MAT_USER_DEFINED_MATERIAL_MODELS`

CARD 1

`MID`	material identification: unique 8-digit number
`RO`	initial mass density of the mixture $\rho_0 = \sum_\alpha n_0^\alpha \rho_{\rm R0}^\alpha$
`MT`	material number for user-defined subroutine call (48, fixed)
`LMC`	length of material constant `cm` array (48, fixed)
`NHV`	number of user history variables excluding $\boldsymbol{F}$ (84, fixed)
`IORTHO`	material is not orthotropic (0, fixed)
`IBULK`	card 3 location for bulk modulus in time step calculation (1, fixed)
`IG`	card 3 location for shear modulus in time step calculation (2, fixed)

CARD 2

`IVECT`	vectorized material model not implemented (0, fixed)
`IFAIL`	independent failure flag not implemented (0, fixed)
`ITHERM`	temperature implemented (1, fixed)
`IHYPER`	deformation gradient $\boldsymbol{F}$ stored in `hsv` vector (1, fixed)
`IEOS`	separate equation of state not implemented (0, fixed)
`LMCA`	length of added material constant `cma` array (24, fixed)

CARD 3

`BULK`	mixture isentropic bulk modulus used by `LS-DYNA` in Δt estimate
`SHEAR`	mixture isotropic shear modulus used by `LS-DYNA` in Δt estimate
`muS`	matrix shear modulus μ_{S}
`aS`	matrix shear stiffening multiplier a_{S}
`kS`	matrix shear stiffening exponent k_{S}
`muk`	fiber shear modulus μ_k
`kk`	fiber exponential stiffening factor k_k
`theta0`	reference and initial temperature θ_0

CARD 4

`n0`	solid volume fraction n_0^{s}
`rhoR`	solid isolated mass density $\rho_{\mathrm{R0}}^{\mathrm{s}}$
`B0`	solid isothermal bulk modulus B_θ^{s}
`Bp`	solid pressure derivative of bulk modulus $B_{\theta\mathrm{p}}^{\mathrm{s}}$
`kv`	solid exponential bulk stiffening factor $k_{\mathrm{V}}^{\mathrm{s}}$
`cv`	solid specific heat at constant strain/volume c_ϵ^{s}
`gruneis`	solid Grüneisen parameter γ_0^{s}
`pR0`	ambient reference pressure p_{R}^{α} for all phases (e.g., 1.0 atm)

CARD 5

`n0`	fluid volume fraction n_0^{f}
`rhoR`	fluid isolated mass density $\rho_{\mathrm{R0}}^{\mathrm{f}}$
`B0`	fluid isothermal bulk modulus B_θ^{f}
`Bp`	fluid pressure derivative of bulk modulus $B_{\theta\mathrm{p}}^{\mathrm{f}}$
`kv`	fluid exponential bulk stiffening factor $k_{\mathrm{V}}^{\mathrm{f}}$
`cv`	fluid specific heat at constant strain/volume c_ϵ^{f}
`gruneis`	fluid Grüneisen parameter γ_0^{f}
`pcav`	fluid cavitation pressure: if nonzero, max allowed value of $-p_{\mathrm{V}}^{\mathrm{f}}/n_0^{\mathrm{f}}$

CARD 6

`kappa1`	dispersion factor κ_k for $k = 1$; if negative, families $k = 1, 2$ disabled
`iota11`	fiber orientation director vector X_1-component $(\iota_k)_1$ for $k = 1$

`iota12`	fiber orientation director vector X_2-component $(\iota_k)_2$ for $k = 1$
`iota13`	fiber orientation director vector X_3-component $(\iota_k)_3$ for $k = 1$
`kappa2`	dispersion factor κ_k for $k = 2$; if negative, family $k = 2$ disabled
`iota21`	fiber orientation director vector X_1-component $(\iota_k)_1$ for $k = 2$
`iota22`	fiber orientation director vector X_2-component $(\iota_k)_2$ for $k = 2$
`iota23`	fiber orientation director vector X_3-component $(\iota_k)_3$ for $k = 2$

CARD 7

`betaM1`	matrix viscoelastic stiffening factor $\beta_{\mathrm{S}1}$
`betaM2`	matrix viscoelastic stiffening factor $\beta_{\mathrm{S}2}$
`tauM1`	matrix viscoelastic relaxation time $\tau_{\mathrm{S}1}$
`tauM2`	matrix viscoelastic relaxation time $\tau_{\mathrm{S}2}$
`betaF1`	fiber viscoelastic stiffening factor $\beta_{\Phi k,1}$ (equal for $k = 1, 2$)
`betaF2`	fiber viscoelastic stiffening factor $\beta_{\Phi k,2}$ (equal for $k = 1, 2$)
`tauF1`	fiber viscoelastic relaxation time $\tau_{\Phi k,1}$ (equal for $k = 1, 2$)
`tauF2`	fiber viscoelastic relaxation time $\tau_{\Phi k,2}$ (equal for $k = 1, 2$)

CARD 8

`dmgflag`	set to 1. to enable damage modeling, or set to 0. for no tissue damage
`dthresh`	normalized damage threshold $\bar{W}_\chi/\mu_{\mathrm{S}} = (W_{\chi k}/\mu_{\mathrm{S}}) \cdot (\bar{E}_{\mathrm{C}}/E_{\mathrm{C}k})$
`Ematrix`	matrix cohesive energy $\bar{E}_{\mathrm{C}}$
`Efibrat`	ratio of fiber to matrix cohesive energy $E_{\mathrm{C}k}/\bar{E}_{\mathrm{C}}$ for all k
`viscdmg`	viscosity time scale for fracture kinetics $\bar{\beta} = \beta_k$ for all k
`vartheta`	phase-field fracture degradation exponent $\bar{\vartheta} = \vartheta_k$ for all k
`erem`	remnant strain at rupture $\bar{\epsilon} = \tilde{\epsilon}_k$ for all k
`ralpha`	non-Euclidean metric scaling factor $\bar{r} = \tilde{r}_k$ for all k

CARD 9

`injflag`	set to 0. for no injury prediction, 1. to enact injury increase from total strain energy,[1] 2. for injury from tensile volumetric energy plus deviatoric energy, or 3. for injury from deviatoric energy only
`ithresh`	normalized injury threshold $\bar{W}_{\chi\mathrm{I}}/\bar{W}_\chi = W_{\chi\mathrm{I}k}/W_{\chi k}$ for all k
`npower`	user-specified solution control variable for damage and injury update

`numiter`	user-specified convergence iterations for damage and injury update*
`cl`	linear shock viscosity coefficient c_l
`cq`	quadratic shock viscosity coefficient c_q
`dDmax`	user-specified max allowed $\dot{\bar{D}}\Delta t$ and $\dot{D}_k\Delta t$ in single increment Δt (only applies if $\bar{\beta} = \beta_k > 0$)
`tenflag`	set to 0. for no dilatational energy contribution to matrix damage and no fiber stress switch-off in compression, 1. for dilatational energy contribution to matrix damage and fiber stress switch-off,[1] 2. for dilatational energy contribution but no fiber stress switch-off, 3. for no dilatational energy contribution but with fiber stress switch-off

CARD 10

`tmpflag`	set to 1. for (e.g., adiabatic) temperature update or to 0. for isothermal
`Pactmax`	max active isometric fiber stress $P_{0k}n_0^s$ for $k = 1, 2$; inactive if 0.
`omegaI`	exponential active stress decay from injury (see Eq. 4.2 in article[1])
`b0`	zeroth-order b_0 in active stress function φ_A (see Eq. 4.1 in article[1])
`b1`	first-order b_1 in active stress function φ_A (see Eq. 4.1 in article[1])
`b2`	second-order b_2 in active stress function φ_A (see Eq. 4.1 in article[1])
`b3`	third-order b_3 in active stress function φ_A (see Eq. 4.1 in article[1])
`b4`	fourth-order b_4 in active stress function φ_A (see Eq. 4.1 in article[1])

CARD 11

`tact0`	starting time t_{A0} for possible muscle activation
`tact1`	ending time t_{A1} for possible muscle activation
`d0`	constant term d_0 in activation function of Equation 1
`d1`	linear term d_1 in activation function of Equation 1
`d2`	quadratic term d_2 in activation function of Equation 1
`d3`	sinusoidal magnitude d_3 in activation function of Equation 1
`d4`	sinusoidal phase lag d_4 in activation function of Equation 1
`d5`	sinusoidal frequency d_5 in activation function of Equation 1

*Reducing `numiter` speeds up simulations but decreases accuracy of damage and injury predictions. If `npower` equals 1.0, then accuracy of rate-independent damage and injury models is $\pm 0.5/$`numiter`.

Card 1	1	2	3	4	5	6	7	8
Variable	MID	RO	MT	LMC	NHV	IORTHO	IBULK	IG
Required (bold font)	user-prescribed	see text	**48**	**48**	**84**	**0**	**1**	**2**
Type	A8	F	I	I	I	I	I	I

Card 2	1	2	3	4	5	6	7	8
Variable	IVECT	IFAIL	ITHERM	IHYPER	IEOS	LMCA		
Required	**0**	**0**	**1**	**1**	**0**	**24**		
Type	I	I	I	I	I	I		

Card 3	1	2	3	4	5	6	7	8
Variable [units]	BULK [Pa]	SHEAR [Pa]	muS [Pa]	aS [none]	kS [none]	muk [Pa]	kk [none]	theta0 [K]
Suggested	3.17E+09	1.0E+05	1.0E+03	20.0	0.5	1.5E+03	3.2	310.0
Type	F	F	F	F	F	F	F	F

Card 4	9	10	11	12	13	14	15	16
Variable [units]	n0 [none]	rhoR [kg/m^3]	B0 [Pa]	Bp [none]	kv [none]	cv [J/kg K]	gruneis [none]	pR0 [Pa]
Suggested	0.90	1103.3	3.17E+09	8.0	6.0	3.25E+03	0.313	1.013E+05
Type	F	F	F	F	F	F	F	F

Card 5	17	18	19	20	21	22	23	24
Variable [units]	n0 [none]	rhoR [kg/m^3]	B0 [Pa]	Bp [none]	kv [none]	cv [J/kg K]	gruneis [none]	pcav [Pa]
Suggested	0.10	1030.0	2.18E+09	6.96	7.0	3.96E+03	0.132	8.9E+06
Type	F	F	F	F	F	F	F	F

Card 6	25	26	27	28	29	30	31	32
Variable [units]	kappa1 [none]	iota11 [none]	iota12 [none]	iota13 [none]	kappa2 [none]	iota21 [none]	iota22 [none]	iota23 [none]
Suggested	0.0	1.0	0.0	0.0	−1.0	0.0	1.0	0.0
Type	F	F	F	F	F	F	F	F

Card 7	33	34	35	36	37	38	39	40
Variable [units]	betaM1 [none]	betaM2 [none]	tauM1 [sec]	tauM2 [sec]	betaF1 [none]	betaF2 [none]	tauF1 [sec]	tauF2 [sec]
Suggested	2.0	0.0	2.0E−02	1.0E−05	2.0	0.0	2.0E−02	1.0E−05
Type	F	F	F	F	F	F	F	F

Card 8	41	42	43	44	45	46	47	48
Variable [units]	dmgflag [none]	dthresh [none]	Ematrix [Pa]	Efibrat [none]	viscdmg [sec]	vartheta [none]	erem [none]	ralpha [none]
Suggested	1.0	5.0	2.65E+03	1.0	0.0	2.0	0.2	2.0
Type	F	F	F	F	F	F	F	F

Card 9	49	50	51	52	53	54	55	56
Variable [units]	injflag [none]	ithresh [none]	npower [none]	numiter [none]	cl [none]	cq [none]	dDmax [none]	tenflag [none]
Suggested	1.0	0.022	1.0	100.0	0.06	1.5	1.0	1.0
Type	F	F	F	F	F	F	F	F

Card 10	57	58	59	60	61	62	63	64
Variable [units]	tmpflag [none]	Pactmax [Pa]	omegal [none]	b0 [none]	b1 [none]	b2 [none]	b3 [none]	b4 [none]
Suggested	1.0	6.7E+04	9.5	−3.7	8.156	−3.74	0.144	0.024
Type	F	F	F	F	F	F	F	F

Card 11	65	66	67	68	69	70	71	72
Variable [units]	tact0 [sec]	tact1 [sec]	d0 [none]	d1 [none]	d2 [none]	d3 [none]	d4 [radian]	d5 [rad/sec]
Suggested	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0
Type	F	F	F	F	F	F	F	F

3. Sample Input File

An example input file invoking the user-material model in `LS-DYNA` syntax follows subsequently. The first unique feature of this file is the material history outputs requested for the first nine entries of `hsv`—θ, $\bar{D}$, D_k ($k = 1, 2$), $\bar{I}$, I_k ($k = 1, 2$), and $\tilde{\sigma}_{\mathrm{A}k}$ ($k = 1, 2$)—as well as all nine components of the deformation gradient $\boldsymbol{F}$. The second unique feature is specification of the user-defined (skeletal muscle) material model and parameters as described in Section 2 of this technical note. Other standard features of the `LS-DYNA` input file are documented in the manuals.[2]

The input file for a one-element mesh is provided in what follows next. Boundary conditions compress a single hexahedral element of unit dimensions by 10% in the X_1-direction over a total time interval of 1 s. The material comprises 90% solid and 10% fluid, with the former encompassing one non-dispersed fiber family (i.e., $\kappa_1 = 0$) aligned in the direction of compression: $\boldsymbol{\iota}_1 = (1, 0, 0)$.

The initial time step is artificially set to an extremely small number to enable printing of output diagnostics over many increments. The space–time domain, loading conditions, and material properties can be adjusted, if need be, to model various 1-D problems as analyzed in Section 4 of the main journal article.[1]

```
*KEYWORD
*TITLE
single 8-node hexahedral finite element of skeletal muscle: user material 48
$--------+---------+---------+---------+---------+---------+---------+---------+
*CONTROL_TERMINATION
$   ENDTIM
    1.0E+0
$--------+---------+---------+---------+---------+---------+---------+---------+
*CONTROL_TIMESTEP
$   DTINIT    TSSFAC
    0.0E+0      0.10
$--------+---------+---------+---------+---------+---------+---------+---------+
*DATABASE_BINARY_D3PLOT
$     FREQ
    1.0E-2
$--------+---------+---------+---------+---------+---------+---------+---------+
*DATABASE_EXTENT_BINARY
$    NEIHP     NEIPS    MAXINT    STRFLG    SIGFLG    EPSFLG    RLTFLG    ENGFLG
        93        93         3         1         1         1         1         1
$   CMPFLG    IEVERP    BEAMIP     DCOMP      SHGE     STSSZ    N3THDT   IALEMAT
         0         0         0         1         1         1         2         1
$  NINTSLD   PKP_SEN      SCLP     HYDRO     MSSCL     THERM    INTOUT    NODOUT
         1         0       1.0         0         0         0
$--------+---------+---------+---------+---------+---------+---------+---------+
*DEFINE_MATERIAL_HISTORIES_NAMES
History,1,48,1,1
THETA
History,2,48,1,1
DMAT
History,3,48,1,1
DFIB1
History,4,48,1,1
DFIB2
History,5,48,1,1
IMAT
History,6,48,1,1
IFIB1
History,7,48,1,1
IFIB2
History,8,48,1,1
SIGACT1
History,9,48,1,1
SIGACT2
History,85,48,1,1
F11
History,86,48,1,1
F21
History,87,48,1,1
F31
History,88,48,1,1
F12
History,89,48,1,1
F22
History,90,48,1,1
F32
History,91,48,1,1
F13
History,92,48,1,1
F23
History,93,48,1,1
F33
*PART
single 3D element
$--------+---------+---------+---------+---------+---------+---------+---------+
$      PID     SECID       MID     EOSID      HGID      GRAV    ADPOPT      TMID
         1         1         1         0         0         0         0         1
*SECTION_SOLID
$    SECID    ELFORM       AET
         1         1         0
$--------+---------+---------+---------+---------+---------+---------+---------+
```

```
*MAT_USER_DEFINED_MATERIAL_MODELS
$--------+---------+---------+---------+---------+---------+---------+---------+
$      MID        RO        MT       LMC       NHV    IORTHO     IBULK        IG
         1    1096.0        48        48        84         0         1         2
$    IVECT     IFAIL    ITHERM    IHYPER      IEOS      LMCA
         0         0         1         1         0        24
$     BULK     SHEAR       muS        aS        kS       muk        kk    theta0
   3.17E+9   1.00E+5   1.00E+3      20.0       0.5     1.5E+3       3.2     310.0
$solid: n0      rhoR        B0        Bp        kv        cv   gruneis       pR0
      0.90    1103.3   3.17E+9       8.0       6.0   3.25E+3     0.313  1.013E+5
$fluid: n0      rhoR        B0        Bp        kv        cv   gruneis      pcav
      0.10    1030.0   2.18E+9      6.96       7.0   3.96E+3     0.132    8.9E+6
$   kappa1    iota11    iota12    iota13    kappa2    iota21    iota22    iota23
       0.0       1.0       0.0       0.0      -1.0       0.0       1.0       0.0
$   betaM1    betaM2     tauM1     tauM2    betaF1    betaF2     tauF1     tauF2
       2.0       0.0    2.0E-2    1.0E-5       2.0       0.0    2.0E-2    1.0E-5
$  dmgflag   dthresh   Ematrix   Efibrat   viscdmg  vartheta      erem    ralpha
       1.0       5.0   2.65E+3       1.0       0.0       2.0       0.2       2.0
$  injflag   ithresh    npower   numiter        cl        cq     dDmax   tenflag
       1.0     0.022       1.0      100.      0.06       1.5       1.0       1.0
$  tmpflag   Pactmax    omegaI        b0        b1        b2        b3        b4
       1.0    6.7E+4       9.5      -3.7     8.156     -3.74     0.144     0.024
$    tact0     tact1        d0        d1        d2        d3        d4        d5
       0.0    1.0E+0       1.0       0.0       0.0       0.0       0.0       0.0
$--------+---------+---------+---------+---------+---------+---------+---------+
*NODE
$------+---------------+---------------+---------------+-------+-------+-------+
$    NID               X               Y               Z      TC      RC
       1              0.              0.              0.       7       7
       2              1.              0.              0.       5       0
       3              1.              1.              0.       3       0
       4              0.              1.              0.       6       0
       5              0.              0.              1.       4       0
       6              1.              0.              1.       2       0
       7              1.              1.              1.       0       0
       8              0.              1.              1.       1       0
*SET_NODE_GENERAL
$--------+---------+---------+---------+---------+---------+---------+---------+
$#     SID       DA1       DA2       DA3       DA4    SOLVER
         1         0         0         0         0      MECH
$#  OPTION        E1        E2        E3        E4        E5        E6        E7
      NODE         1         4         5         8
*SET_NODE_GENERAL
$--------+---------+---------+---------+---------+---------+---------+---------+
$#     SID       DA1       DA2       DA3       DA4    SOLVER
         2         0         0         0         0      MECH
$#  OPTION        E1        E2        E3        E4        E5        E6        E7
      NODE         2         3         6         7
*SET_NODE_GENERAL
$--------+---------+---------+---------+---------+---------+---------+---------+
$#     SID       DA1       DA2       DA3       DA4    SOLVER
         3         0         0         0         0      MECH
$#  OPTION        E1        E2        E3        E4        E5        E6        E7
       ALL
$--------+---------+---------+---------+---------+---------+---------+---------+
*SET_PART
$--------+---------+---------+---------+---------+---------+---------+---------+
$#     SID       DA1       DA2       DA3       DA4    SOLVER
         1         0         0         0         0      MECH
$#     PID
         1
*ELEMENT_SOLID
$------+-------+-------+-------+-------+-------+-------+-------+-------+-------+
$    EID     PID      N1      N2      N3      N4      N5      N6      N7      N8
       1       1       1       2       3       4       5       6       7       8
$--------+---------+---------+---------+---------+---------+---------+---------+
*BOUNDARY_PRESCRIBED_MOTION_SET
$#  TYPEID       DOF       VAD      LCID        SF       VID     DEATH     BIRTH
         1         1         0         1       1.0
*BOUNDARY_PRESCRIBED_MOTION_SET
```

```
$#  TYPEID       DOF       VAD      LCID        SF       VID     DEATH     BIRTH
         2         1         0         2      -0.1
*BOUNDARY_PRESCRIBED_MOTION_SET
$#  TYPEID       DOF       VAD      LCID        SF       VID     DEATH     BIRTH
         3         2         0         1       1.0
*BOUNDARY_PRESCRIBED_MOTION_SET
$#  TYPEID       DOF       VAD      LCID        SF       VID     DEATH     BIRTH
         3         3         0         1       1.0
*DEFINE_CURVE
$--------+---------+---------+---------+---------+---------+---------+---------+
$     LCID      SIDR       SFA       SFO      OFFA      OFFO    DATTYP
         1
$-----------------+-------------------+
$                 A1                  O1
                 0.0                 0.0
                 1.0                 0.0
*DEFINE_CURVE
$--------+---------+---------+---------+---------+---------+---------+---------+
$     LCID      SIDR       SFA       SFO      OFFA      OFFO    DATTYP
         2
$-----------------+-------------------+
$                 A1                  O1
                 0.0                 1.0
                 1.0                 1.0
*END
```

4. References

1. Clayton J, Hampton C. Dynamic damage in active and passive skeletal muscle: a continuum mechanical model. International Journal of Engineering Science. 2026;221:104472.
2. Hallquist J. LS-DYNA User's Manual R15. Livermore Software Technology Corporation; 2024.
3. Clayton J. User documentation for a liver constitutive model. DEVCOM Army Research Laboratory (US); 2025. Report No.: ARL-TN-1273.
4. Clayton J. Modeling lung tissue dynamics and injury under pressure and impact loading. Biomechanics and Modeling in Mechanobiology. 2020;19:2603–2626.
5. Clayton J, Freed A. A constitutive model for lung mechanics and injury applicable to static, dynamic, and shock loading. Mechanics of Soft Materials. 2020;2:3.
6. Clayton J, Banton R, Goertz A. A continuum mechanical model of the human lung: implementation and parameterization. DEVCOM Army Research Laboratory (US); 2020. Report No.: ARL-TR-9138.
7. Freed A, Clayton J. Coordinate indexing strategies for the Laplace stretch in two and three dimensions. DEVCOM Army Research Laboratory (US); 2022. Report No.: ARL-TR-9530.
8. Clayton J. Modeling dynamic impact, shock waves, and injury in liver tissue with a constrained mixture theory. Biomechanics and Modeling in Mechanobiology. 2025;24:1735–1766.
9. Hampton C, Kleinberger M. Material models for the human torso finite element model. Army Research Laboratory (US); 2018. Report No.: ARL-TR-8338.
10. Regueiro R, Zhang B, Wozniak S. Large deformation dynamic three-dimensional coupled finite element analysis of soft biological tissues treated as biphasic porous media. Computer Modeling in Engineering Sciences (CMES). 2014;98:1–39.
11. Clayton J. Analysis of shock waves in a mixture theory of a thermoelastic solid and fluid with distinct temperatures. International Journal of Engineering Science. 2022;175:103675.

12. Clayton J. Generalized Finsler geometry and the anisotropic tearing of skin. Symmetry. 2023;15:1828.

13. Clayton J. Universal phase-field mixture representation of thermodynamics and shock wave mechanics in porous soft biologic continua. Physical Review E. 2024;110:035001.

14. Clayton J. A universal continuum theory and shock wave analysis for biologic solids and fluids. DEVCOM Army Research Laboratory (US); 2024. Report No.: ARL-TR-10010.

15. Irwin Z, Clayton J, Regueiro R. A large deformation multiphase continuum mechanics model for shock loading of soft porous materials. International Journal for Numerical Methods in Engineering. 2024;125:e7411.

16. Clayton J. Nonlinear soft-tissue elasticity, remodeling, and degradation described by an extended Finsler geometry. Journal of Elasticity. 2025;157:15.

17. Clayton J, Lloyd J. Numerical models for constitutive behaviors of ferrous metals. DEVCOM Army Research Laboratory (US); 2023. Report No.: ARL-TR-9776.

18. Holzapfel G, Ogden R. Constitutive modelling of passive myocardium: a structurally based framework for material characterization. Philosophical Transactions of the Royal Society A. 2009;367:3445–3475.

19. Nagy A, Benson D, Kaul V, Palmer M. Constitutive modeling of biological soft tissues. 15th International LS-DYNA Users Conference. Detroit (MI), 2018.

20. Clayton J. Nonlinear mechanics of crystals. Springer; 2011.

List of Symbols, Abbreviations, and Acronyms

TERMS

1-D	one-dimensional
3-D	three-dimensional
EOS	equation of state
FE	finite element
SI	International System of Units

MATHEMATICAL SYMBOLS

$(\square)^{\alpha}$	quantity for constituent or phase α
$(\square)^{\mathrm{s}}$	quantity for solid constituent
$(\square)^{\mathrm{f}}$	quantity for fluid constituent
$(\square)_k$	quantity for fiber family k
$(\square)_{\mathrm{D}}$	quantity for damage model
$(\square)_{\mathrm{F}}$	quantity for fiber hyperelasticity
$(\square)_{\mathrm{R}}$	quantity for isolated (i.e., real) constituent
$(\square)_{\mathrm{S}}$	quantity for deviatoric response
$(\square)_{\mathrm{V}}$	quantity for volumetric response
$(\square)_{\mathrm{A}}$	quantity for active response
$(\square)_{\Gamma}$	quantity for matrix viscoelasticity
$(\square)_{\Phi}$	quantity for fiber viscoelasticity
$(\square)_0$	quantity typically defined in global reference configuration
$(\square)_*$	quantity in local reference state where properties measured
$(\square)_\star$	quantity measuring transition from state at t_* to current t
$(\dot{\square})$	material time derivative with respect to mixture
a_{S}	nonlinear shear stiffening constant
B_θ	isothermal bulk modulus
$B_{\theta \mathrm{p}}$	pressure derivative of isothermal bulk modulus
c_ϵ	specific heat per unit mass at constant strain
c_{l}	linear bulk viscosity coefficient
c_{q}	quadratic bulk viscosity coefficient
$\boldsymbol{C}$	right Cauchy–Green tensor
$\boldsymbol{d}$	spatial deformation rate tensor
D	order parameter or damage measure for fiber fracture

$\bar{D}$	order parameter for matrix fracture or fluid cavitation
E_{C}	cohesive energy of fibers per unit reference volume
$\bar{E}_{\mathrm{C}}$	cohesive energy of matrix or fluid per unit reference volume
$\boldsymbol{F}$	deformation gradient
I	scalar injury measure for fiber family
$\bar{I}$	scalar injury measure for matrix or fluid
J	Jacobian determinant of deformation gradient
k	fiber exponential stiffening constant
k_{S}	shear exponential stiffening constant
k_{V}	volumetric exponential stiffening constant
n_0	referential constituent volume fraction
$n_\star$	mapped constituent volume fraction
p	Cauchy pressure
$\boldsymbol{Q}$	conjugate stress to viscoelastic configurational state variable
$\tilde{r}$	Finsler metric exponential constant for fibers
$\bar{r}$	Finsler metric exponential constant for matrix or fluid
t	time
W_χ	energy threshold for matrix or fiber damage initiation
$W_{\chi\mathrm{I}}$	energy threshold for matrix or fiber damage initiation
$\boldsymbol{x}$	spatial (i.e., Eulerian) coordinates
$\boldsymbol{X}$	referential (i.e., Lagrangian or material) coordinates
β	viscoelastic stiffness factor or viscous time for fracture kinetics
Δ	transient muscle activation function
$\bar{\epsilon}$	remnant strain for matrix
$\tilde{\epsilon}$	remnant strain for fibers
γ_0	Grüneisen parameter (scalar)
$\boldsymbol{\Gamma}$	viscoelastic configurational state variable
μ	shear modulus
β	viscosity or kinetic parameter
θ	temperature
ϑ	damage degradation exponent
ρ	spatial mass density
ρ_0	referential mass density
$\rho_{\mathrm{R}0}$	real mass density of isolated constituent at 1 atm
$\boldsymbol{\sigma}$	total Cauchy stress tensor
τ	viscoelastic relaxation time
Ψ	Helmholtz free energy per unit volume

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
1 (PDF)	DEVCOM ARL FCDD RLD DCI TECH LIB