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XML Reference

Introduction

This chapter is the reference manual for the MJCF modeling language used in MuJoCo.

XML schema

The table below summarizes the XML elements and their attributes in MJCF. Note that all information in MJCF is entered through elements and attributes. Text content in elements is not used; if present, the parser ignores it.

▶ **Expand schema table**

Attribute types

Each attribute has a data type enforced by the parser. The available data types are:

string	An arbitrary string, usually specifying a file name or a user-defined name of a model element.
int(N)	An array of N integers. If N is omitted it equals 1.
real(N)	An array of N real-valued numbers. If N is omitted it equals 1.
[…]	Keyword attribute. The list of valid keywords is given in brackets.

For array-type attributes, the length of the array is enforced by the parser unless specified otherwise in the reference documentation below.
In addition to having a data type, attributes can be required or optional. Optional attributes can have internal defaults or not. Optional attributes that do not have internal defaults are initialized in a special undefined state. This state is different from any valid setting that can be entered in the XML. This mechanism enables the compiler to determine if the attribute has been "touched" by the user, either explicitly or through defaults, and take appropriate action. Some attributes have internal defaults (usually 0) which are not actually allowed by the compiler. When such attributes become relevant in a given context, they must be set to allowed values.

required	The attribute is required by the parser. If it is not present the parser will generate an error.
optional	The attribute is optional. There is no internal default. The attribute is initialized in the undefined state.
"…"	The attribute is optional. The internal default is given in quotes.

In the reference documentation below the attribute name is shown in boldface, followed by its data type, followed by the required/optional status including the internal default if any. For example, the attribute angle is a keyword attribute whose value can be "radian" or "degree". It is an optional attribute and has internal default "degree". Therefore it will appear in the reference documentation as

angle: [radian, degree], "degree"

MJCF Reference

MJCF files have a unique top-level element mujoco. The next-level elements are referred to as *sections*. They are all optional. Some sections are merely used for grouping and have no attributes. Sections can be repeated, to facilitate merging of models via the include element. The *order* of attributes within an element can be arbitrary. The order of child elements within a parent element can also be arbitrary, with four exceptions:

- The order of joint elements within a body matters because joint transformations are performed in sequence.
- The order of elements in a spatial tendon matters because it determines the sequence of objects that the tendon passes through or wraps around.
- The order of repeated sections matters when the same attribute is set multiple times to different values. In that case the last setting takes effect for the entire model.
- The order of multiple actuator shortcuts in the same defaults class matters, because each shortcut sets the attributes of the single general element in that defaults class, overriding the previous settings.

In the remainder of this chapter we describe all valid MJCF elements and their attributes. Some elements can be used in multiple contexts, in which case their meaning depends on the parent element. This is why we always show the parent as a prefix in the documentation below.

include (*)

This element does not strictly speaking belong to MJCF. Instead it is a meta-element, used to assemble multiple XML files in a single document object model (DOM) before parsing. The included file must be a valid XML file with a unique top-level element. This top-level element is removed by the parser, and the elements below it are inserted at the location of the **include** element. At least one element must be inserted as a result of this procedure. The **include** element can be used where ever an XML element is expected in the MJFC file. Nested includes are allowed, however a given XML file can be included at most once in the entire model. After all the included XML files have been assembled into a single DOM, it must correspond to a valid MJCF model. Other than that, it is up to the user to decide how to use includes and how to modularize large files if desired.

file: string, required

v: stable

The name of the XML file to be included. The file location is relative to the directory of the main MJCF file. If the ↑ Back to top e same directory, it should be prefixed with a relative path.

mujoco (!)

The unique top-level element, identifying the XML file as an MJCF model file.

model: string, "MuJoCo Model"

The name of the model. This name is shown in the title bar of simulate.cc.

compiler (*)

This element is used to set options for the built-in parser and compiler. After parsing and compilation it no longer has any effect. The settings here are global and apply to the entire model.

autolimits: [false, true], "false"

This attribute affects the behavior of attributes such as "limited" (on <body-joint> or <tendon>), "forcelimited", "ctrllimited", and "actlimited" (on <actuator>). If "true", these attributes are unnecessary and their value will be inferred from the presence of their corresponding "range" attribute. If "false", no such inference will happen: For a joint to be limited, both limited="true" and range="min max" must be specified. In this mode, it is an error to specify a range without a limit.
The default for this option will be set to "true" in an upcoming release.

boundmass: real, "0"

This attribute imposes a lower bound on the mass of each body except for the world body. Setting this attribute to a value greater than 0 can be used as a quick fix for poorly designed models that contain massless moving bodies, such as the dummy bodies often used in URDF models to attach sensors. Note that in MuJoCo there is no need to create dummy bodies.

boundinertia: real, "0"

This attribute imposes a lower bound on the diagonal inertia components of each body except for the world body. Its use is similar to boundmass above.

settotalmass: real, "-1"

If this value is positive, the compiler will scale the masses and inertias of all bodies in the model, so that the total mass equals the value specified here. The world body has mass 0 and does not participate in any mass-related computations. This scaling is performed last, after all other operations affecting the body mass and inertia. The same scaling operation can be applied at runtime to the compiled mjModel with the function mj_setTotalmass.

balanceinertia: [false, true], "false"

A valid diagonal inertia matrix must satisfy A+B>=C for all permutations of the three diagonal elements. Some poorly designed models violate this constraint, which will normally result in a compile error. If this attribute is set to "true", the compiler will silently set all three diagonal elements to their average value whenever the above condition is violated.

strippath: [false, true], "false" for MJCF, "true" for URDF

When this attribute is "true", the parser will remove any path information in file names specified in the model. This is useful for loading models created on a different system using a different directory structure.

coordinate: [local, global], "local" for MJCF, always "local" for URDF

This attribute specifies whether the frame positions and orientations in the MJCF model are expressed in local or global coordinates; recall Coordinate frames. The compiler converts global into local coordinates, and mjModel always uses local coordinates. For URDF models the parser sets this attribute to "local" internally, regardless of the XML setting.

angle: [radian, degree], "degree" for MJCF, always "radian" for URDF

This attribute specifies whether the angles in the MJCF model are expressed in units of degrees or radians. The compiler converts degrees into radians, and mjModel always uses radians. For URDF models the parser sets this attribute to "radian" internally, regardless of the XML setting.

fitaabb: [false, true], "false"

The compiler is able to replace a mesh with a geometric primitive fitted to that mesh; see geom below. If this attribute is "true", the fitting procedure uses the axis-aligned bounding box (aabb) of the mesh. Otherwise it uses the equivalent-inertia box of the mesh. The type of geometric primitive used for fitting is specified separately for each geom.

eulerseq: string, "xyz"

This attribute specifies the sequence of Euler rotations for all euler attributes of elements that have spatial frames, as explained in Frame orientations. This must be a string with exactly 3 characters from the set {'x', 'y', 'z', 'X', 'Y', 'Z'}. The character at position n determines the axis around which the n-th rotation is performed. Lower case denotes axes that rotate with the frame, while upper case denotes axes that remain fixed in the parent frame. The "rpy" convention used in URDF corresponds to the default "xyz" in MJCF.

meshdir: string, optional

This attribute instructs the compiler where to look for mesh and height field files. The full path to a file is determined as follows. If the strippath attribute described above is "true", all path information from the file name is removed. The following checks are then applied in order: (1) if the file name contains an absolute path, it is used without further changes; (2) if this attribute is set and contains an absolute path, the full path is the string given here appended with the file name; (3) the full path is the path to the main MJCF model file, appended with the value of this attribute if specified, appended with the file name.

texturedir: string, optional

This attribute is used to instruct the compiler where to look for texture files. It works in the same way as meshdir above.

assetdir: string, optional

This attribute sets the values of both meshdir and texturedir above. Values in the latter attributes take precedence over assetdir.

discardvisual: [false, true], "false" for MJCF, "true" for URDF

This attribute instructs the parser to discard "visual geoms", defined as geoms whose contype and conaffinity attrib [illegible] set to 0. This functionality is useful for models that contain two sets of geoms, one for collisions and the other for visualization. Note that URDF models are usually constructed in this way. It rarely makes sense to have two sets of geoms in the model, especially since MuJoCo uses convex hulls for collisions, so we recommend using this feature to discard redundant geoms. Keep in mind however that geoms considered visual per the above definition can still participate in collisions, if they appear in the explicit list of contact pairs. The parser does not check this list before discarding geoms; it relies solely on the geom attributes to make the determination.

convexhull: [false, true], "true"

If this attribute is "true", the compiler will automatically generate a convex hull for every mesh that is used in at least one non-visual geom (in the sense of the discardvisual attribute above). This is done to speed up collision detection; recall Collision detection section in the Computation chapter. Even if the mesh is already convex, the hull contains edge information that is not present in the mesh file, so it needs to be constructed. The only reason to disable this feature is to speed up re-loading of a model with large meshes during model editing (since the convex hull computation is the slowest operation performed by the compiler). However once model design is finished, this feature should be enabled, because the availability of convex hulls substantially speeds up collision detection with large meshes.

usethread: [false, true], "true"

If this attribute is "true", the model compiler will run in multi-threaded mode. Currently multi-threading is only used when computing the length ranges of actuators, but in the future additional compiler phases may be multi-threaded.

fusestatic: [false, true], "false" for MJCF, "true" for URDF

This attribute controls a compiler optimization feature where static bodies are fused with their parent, and any elements defined in those bodies are reassigned to the parent. This feature can only be used in models which do not have elements capable of named references inside the kinematic tree - namely skins, contact pairs, excludes, tendons, actuators, sensors, tuples, cameras, lights. If a model has any these elements, fusestatic does nothing even if enabled. This optimization is particularly useful when importing URDF models which often have many dummy bodies, but can also be used to optimize MJCF models. After optimization, the new model has identical kinematics and dynamics as the original but is faster to simulate.

inertiafromgeom: [false, true, auto], "auto"

This attribute controls the automatic inference of body masses and inertias from geoms attached to the body. If this setting is "false", no automatic inference is performed. In that case each body must have explicitly defined mass and inertia with the inertial element, or else a compile error will be generated. If this setting is "true", the mass and inertia of each body will be inferred from the geoms attached to it, overriding any values specified with the **inertial** element. The default setting "auto" means that masses and inertias are inferred automatically only when the **inertial** element is missing in the body definition. One reason to set this attribute to "true" instead of "auto" is to override inertial data imported from a poorly designed model. In particular, a number of publicly available URDF models have seemingly arbitrary inertias which are too large compared to the mass. This results in equivalent inertia boxes which extend far beyond the geometric boundaries of the model. Note that the built-in OpenGL visualizer can render equivalent inertia boxes.

exactmeshinertia: [false, true], "false"

If this attribute is set to false, computes mesh inertia with the legacy algorithm, which is exact only for convex meshes. If set to true, it is exact for any closed mesh geometry.

inertiagrouprange: int(2), "0 5"

This attribute specifies the range of geom groups that are used to infer body masses and inertias (when such inference is enabled). The group attribute of geom is an integer. If this integer falls in the range specified here, the geom will be used in the inertial computation, otherwise it will be ignored. This feature is useful in models that have redundant sets of geoms for collision and visualization. Note that the world body does not participate in the inertial computations, so any geoms attached to it are automatically ignored. Therefore it is not necessary to adjust this attribute and the geom-specific groups so as to exclude world geoms from the inertial computation.

compiler/ lengthrange (?)

This element controls the computation of actuator length ranges. For an overview of this functionality see Length range section. Note that if this element is omitted the defaults shown below still apply. In order to disable length range computations altogether, include this element and set mode="none".

mode: [none, muscle, muscleuser, all], "muscle"

Determines the type of actuators to which length range computation is applied. "none" disables this functionality. "all" applies it to all actuators. "muscle" applies it to actuators whose gaintype or biastype is set to "muscle". "muscleuser" applies it to actuators whose gaintype or biastype is set to either "muscle" or "user". The default is "muscle" because MuJoCo's muscle model requires actuator length ranges to be defined.

useexisting: [false, true], "true"

If this attribute is "true" and the length range for a given actuator is already defined in the model, the existing value will be used and the automatic computation will be skipped. The range is considered defined if the first number is smaller than the second number. The only reason to set this attribute to "false" is to force re-computation of actuator length ranges - which is needed when the model geometry is modified. Note that the automatic computation relies on simulation and can be slow, so saving the model and using the existing values when possible is recommended.

uselimit: [false, true], "false"

If this attribute is "true" and the actuator is attached to a joint or a tendon which has limits defined, these limits will be copied into the actuator length range and the automatic computation will be skipped. This may seem like a good idea but note that in complex models the feasible range of tendon actuators depends on the entire model, and may be smaller than the user-defined limits for that tendon. So the safer approach is to set this to "false", and let the automatic computation discover the feasible range.

accel: real, “20”

This attribute scales ↑ Back to top lied to the simulation in order to push each actuator to its smallest and largest length. The force magnitude is computed so that the resulting joint-space acceleration vector has norm equal to this attribute.

maxforce: real, “0”

The force computed via the accel attribute above can be very large when the actuator has very small moments. Such a force will still produce reasonable acceleration (by construction) but large numbers could cause numerical issues. Although we have never observed such issues, the present attribute is provided as a safeguard. Setting it to a value larger than 0 limits the norm of the force being applied during simulation. The default setting of 0 disables this safeguard.

timeconst: real, “1”

The simulation is damped in a non-physical way so as to push the actuators to their limits without the risk of instabilities. This is done by simply scaling down the joint velocity at each time step. In the absence of new accelerations, such scaling will decrease the velocity exponentially. The timeconst attribute specifies the time constant of this exponential decrease, in seconds.

timestep: real, “0.01”

The timestep used for the internal simulation. Setting this to 0 will cause the model timestep to be used. The latter is not the default because models that can go unstable usually have small timesteps, while the simulation here is artificially damped and very stable. To speed up the length range computation, users can attempt to increase this value.

inttotal: real, “10”

The total time interval (in seconds) for running the internal simulation, for each actuator and actuator direction. Each simulation is initialized at qpos0. It is expected to settle after inttotal time has passed.

inteval: real, “2”

The time interval at the end of the simulation over which length data is collected and analyzed. The maximum (or respectively minimum) length achieved during this interval is recorded. The difference between the maximum and minimum is also recorded and is used as a measure of divergence. If the simulation settles, this difference will be small. If it is not small, this could be because the simulation has not yet settled - in which case the above attributes should be adjusted - or because the model does not have sufficient joint and tendon limits and so the actuator range is effectively unlimited. Both of these conditions cause the same compiler error. Recall that contacts are disabled in this simulation, so joint and tendon limits as well as overall geometry are the only things that can prevent actuators from having infinite length.

tolrange: real, “0.05”

This determines the threshold for detecting divergence and generating a compiler error. The range of actuator lengths observed during inteval is divided by the overall range computed via simulation. If that value is larger than tolrange, a compiler error is generated. So one way to suppress compiler errors is to simply make this attribute larger, but in that case the results could be inaccurate.

option (*)

This element is in one-to-one correspondence with the low level structure mjOption contained in the field mjModel.opt of mjModel. These are simulation options and do not affect the compilation process in any way; they are simply copied into the low level model. Even though mjOption can be modified by the user at runtime, it is nevertheless a good idea to adjust it properly through the XML.

timestep: real, “0.002”

Simulation time step in seconds. This is the single most important parameter affecting the speed-accuracy trade-off which is inherent in every physics simulation. Smaller values result in better accuracy and stability. To achieve real-time performance, the time step must be larger than the CPU time per step (or 4 times larger when using the RK4 integrator). The CPU time is measured with internal timers. It should be monitored when adjusting the time step. MuJoCo can simulate most robotic systems a lot faster than real-time, however models with many floating objects (resulting in many contacts) are more demanding computationally. Keep in mind that stability is determined not only by the time step but also by the Solver parameters; in particular softer constraints can be simulated with larger time steps. When fine-tuning a challenging model, it is recommended to experiment with both settings jointly. In optimization-related applications, real-time is no longer good enough and instead it is desirable to run the simulation as fast as possible. In that case the time step should be made as large as possible.

apirate: real, “100”

This parameter determines the rate (in Hz) at which an external API allows the update function to be executed. This mechanism is used to simulate devices with limited communication bandwidth. It only affects the socket API and not the physics simulation.

impratio: real, “1”

This attribute determines the ratio of frictional-to-normal constraint impedance for elliptic friction cones. The setting of solimp determines a single impedance value for all contact dimensions, which is then modulated by this attribute. Settings larger than 1 cause friction forces to be “harder” than normal forces, having the general effect of preventing slip, without increasing the actual friction coefficient. For pyramidal friction cones the situation is more complex because the pyramidal approximation mixes normal and frictional dimensions within each basis vector; but the overall effect of this attribute is qualitatively similar.

gravity: real(3), “0 0 -9.81”

Gravitational acceleration vector. In the default world orientation the Z-axis points up. The MuJoCo GUI is organized around this convention (both the camera and perturbation commands are based on it) so we do not recommend deviating from it.

wind: real(3), “0 0 0”

Velocity vector of the medium (i.e., wind). This vector is subtracted from the 3D translational velocity of each body, and the result is used to compute viscous, lift and drag forces acting on

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the body; recall Passive forces in the Computation chapter. The magnitude of these forces scales with the value wo attributes.

magnetic: real(3), "0 -0.5 0"

Global magnetic flux. This vector is used by magnetometer sensors, which are defined as sites and return the magnetic flux at the site position expressed in the site frame.

density: real, "0"

Density of the medium, not to be confused with the geom density used to infer masses and inertias. This parameter is used to simulate lift and drag forces, which scale quadratically with velocity. In SI units the density of air is around 1.2 while the density of water is around 1000 depending on temperature. Setting density to 0 disables lift and drag forces.

viscosity: real, "0"

Viscosity of the medium. This parameter is used to simulate viscous forces, which scale linearly with velocity. In SI units the viscosity of air is around 0.00002 while the viscosity of water is around 0.0009 depending on temperature. Setting viscosity to 0 disables viscous forces. Note that the default Euler integrator handles damping in the joints implicitly – which improves stability and accuracy. It does not presently do this with body viscosity. Therefore, if the goal is merely to create a damped simulation (as opposed to modeling the specific effects of viscosity), we recommend using joint damping rather than body viscosity, or switching to the implicit integrator.

o_margin: real, "0"

This attribute replaces the margin parameter of all active contact pairs when Contact override is enabled. Otherwise MuJoCo uses the element-specific margin attribute of geom or pair depending on how the contact pair was generated. See also Collision detection in the Computation chapter. The related gap parameter does not have a global override.

o_solref, o_solimp

These attributes replace the solref and solimp parameters of all active contact pairs when contact override is enabled. See Solver parameters for details.

integrator: [Euler, RK4, implicit], "Euler"

This attribute selects the numerical integrator to be used. Currently the available integrators are the semi-implicit Euler method, the fixed-step 4-th order Runge Kutta method, and the Implicit-in-velocity Euler method.

collision: [all, predefined, dynamic], "all"

This attribute specifies which geom pairs should be checked for collision; recall Collision detection in the Computation chapter. "predefined" means that only the explicitly-defined contact pairs are checked. "dynamic" means that only the contact pairs generated dynamically are checked. "all" means that the contact pairs from both sources are checked.

cone: [pyramidal, elliptic], "pyramidal"

The type of contact friction cone. Elliptic cones are a better model of the physical reality, but pyramidal cones sometimes make the solver faster and more robust.

jacobian: [dense, sparse, auto], "auto"

The type of constraint Jacobian and matrices computed from it. Auto resolves to dense when the number of degrees of freedom is up to 60, and sparse over 60.

solver: [PGS, CG, Newton], "Newton"

This attribute selects one of the constraint solver algorithms described in the Computation chapter. Guidelines for solver selection and parameter tuning are available in the Algorithms section above.

iterations: int, "100"

Maximum number of iterations of the constraint solver. When the warmstart attribute of flag is enabled (which is the default), accurate results are obtained with fewer iterations. Larger and more complex systems with many interacting constraints require more iterations. Note that mjData.solver contains statistics about solver convergence, also shown in the profiler.

tolerance: real, "1e-8"

Tolerance threshold used for early termination of the iterative solver. For PGS, the threshold is applied to the cost improvement between two iterations. For CG and Newton, it is applied to the smaller of the cost improvement and the gradient norm. Set the tolerance to 0 to disable early termination.

noslip_iterations: int, "0"

Maximum number of iterations of the Noslip solver. This is a post-processing step executed after the main solver. It uses a modified PGS method to suppress slip/drift in friction dimensions resulting from the soft-constraint model. The default setting 0 disables this post-processing step.

noslip_tolerance: real, "1e-6"

Tolerance threshold used for early termination of the Noslip solver.

mpr_iterations: int, "50"

Maximum number of iterations of the MPR algorithm used for convex mesh collisions. This rarely needs to be adjusted, except in situations where some geoms have very large aspect ratios.

mpr_tolerance: real, "1e-6"

Tolerance threshold used for early termination of the MPR algorithm.

option/ flag (?)

This element sets the flags that enable and disable different parts of the simulation pipeline. The actual flags used at runtime are represented as the bits of two integers, namely mjModel.opt.disableflags and mjModel.opt.enableflags, used to disable standard features and enable optional features respectively. The reason for this separation is that setting both integers to 0 restores the default. In the XML we do not make this separation explicit, except for the default attribute values - which are "enable" for flags corresponding to standard features, and "disable" for flags corresponding to optional features. In the documentation below, we explain what happens when the setting is different from its default.

constraint: [disable, enable], "enable"

This flag disables all standard computations related to the constraint solver. As a result, no constraint forces are ↑ Back to top that the next four flags disable the computations related to a specific type of constraint. Both this flag and the type-specific flag must be set to "enable" for a given computation to be performed.

equality: [disable, enable], "enable"

This flag disables all standard computations related to equality constraints.

frictionloss: [disable, enable], "enable"

This flag disables all standard computations related to friction loss constraints.

limit: [disable, enable], "enable"

This flag disables all standard computations related to joint and tendon limit constraints.

contact: [disable, enable], "enable"

This flag disables all standard computations related to contact constraints.

passive: [disable, enable], "enable"

This flag disables the simulation of joint and tendon spring-dampers, fluid dynamics forces, and custom passive forces computed by the mjcb_passive callback. As a result, no passive forces are applied.

gravity: [disable, enable], "enable"

This flag causes the gravitational acceleration vector in mjOption to be replaced with (0 0 0) at runtime, without changing the value in mjOption. Once the flag is re-enabled, the value in mjOption is used.

clampctrl: [disable, enable], "enable"

This flag disables the clamping of control inputs to all actuators, even if the actuator-specific attributes are set to enable clamping.

warmstart: [disable, enable], "enable"

This flag disables warm-starting of the constraint solver. By default the solver uses the solution (i.e., the constraint force) from the previous time step to initialize the iterative optimization. This feature should be disabled when evaluating the dynamics at a collection of states that do not form a trajectory - in which case warm starts make no sense and are likely to slow down the solver.

filterparent: [disable, enable], "enable"

This flag disables the filtering of contact pairs where the two geoms belong to a parent and child body; recall contact selection in the Computation chapter.

actuation: [disable, enable], "enable"

This flag disables all standard computations related to actuator forces, including the actuator dynamics. As a result, no actuator forces are applied to the simulation.

refsafe: [disable, enable], "enable"

This flag enables a safety mechanism that prevents instabilities due to solref[0] being too small compared to the simulation timestep. Recall that solref[0] is the stiffness of the virtual spring-damper used for constraint stabilization. If this setting is enabled, the solver uses max(solref[0], 2*timestep) in place of solref[0] separately for each active constraint.

sensor: [disable, enable], "enable"

This flag disables all computations related to sensors. When disabled, sensor values will remain constant, either zeros if disabled at the start of simulation, or, if disabled at runtime, whatever value was last computed.

override: [disable, enable], "disable"

This flag enables to Contact override mechanism explained above.

energy: [disable, enable], "disable"

This flag enables the computation of kinetic and potential energy, stored in mjData.energy and displayed in the GUI. This feature adds some CPU time but it is usually negligible. Monitoring energy for a system that is supposed to be energy-conserving is one of the best ways to assess the accuracy of a complex simulation.

fwdinv: [disable, enable], "disable"

This flag enables the automatic comparison of forward and inverse dynamics. When enabled, the inverse dynamics is invoked after mj_forward (or internally within mj_step) and the difference in applied forces is recorded in mjData.solver_fwdinv[2]. The first value is the relative norm of the discrepancy in joint space, the next is in constraint space.

sensornoise: [disable, enable], "disable"

This flag enables the simulation of sensor noise. When disabled (which is the default) noise is not added to sensordata, even if the sensors specify non-zero noise amplitudes. When enabled, zero-mean Gaussian noise is added to the underlying deterministic sensor data. Its standard deviation is determined by the noise parameter of each sensor.

multiccd: [disable, enable], "disable" **(experimental feature)**

This flag enables multiple-contact collision detection for geom pairs that use the general-purpose convex-convex collider based on libccd e.g., mesh-mesh collisions. This can be useful when the contacting geoms have a flat surface, and the single contact point generated by the convex-convex collider cannot accurately capture the surface contact, leading to instabilities that typically manifest as sliding or wobbling. Multiple contact points are found by rotating the two geoms by ±1e-3 radians around the tangential axes and re-running the collision function. If a new contact is detected it is added, allowing for up to 4 additional contact points. This feature is currently considered experimental, and both the behavior and the way it is activated may change in the future.

size (*)

This element specifies size parameters that cannot be inferred from the number of elements in the model. Unlike the fields of mjOption which can be modified at runtime, sizes are structural parameters and should not be modified after compilation.

memory: string, "-1"

This attribute specifies the size of memory allocated for dynamic arrays in the `mjData.arena` memory space, in bytes. The default setting of `-1` instructs the compiler to guess how much

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space to allocate. Appending the digits with one of the letters {K, M, G, T, P, E} sets the unit to be {kilo, mega, giga, t -byte, respectively. Thus "16M" means "allocate 16 megabytes of `arena` memory". See the Memory allocation section for details.

njmax: int, "-1" **(legacy)**

This is a deprecated legacy attribute. In versions prior to 2.3.0, it determined the maximum allowed number of constraints. Currently it means "allocate as much memory as would have previously been required for this number of constraints". Specifying both njmax and memory leads to an error.

nconmax: int, "-1" **(legacy)**

This attribute specifies the maximum number of contacts that will be generated at runtime. If the number of active contacts is about to exceed this value, the extra contacts are discarded and a warning is generated. This is a deprecated legacy attribute which prior to version 2.3.0 affected memory allocation. It is kept for backwards compatibillity and debugging purposes.

nstack: int, "-1" **(legacy)**

This is a deprecated legacy attribute. In versions prior to 2.3.0, it determined the maximum size of the stack. After version 2.3.0, if nstack is specified, then the size of `mjData.arena` is `nstack * sizeof(mjtNum)` bytes, plus an additional space for the constraint solver. Specifying both nstack and memory leads to an error.

nuserdata: int, "0"

The size of the field mjData.userdata of mjData. This field should be used to store custom dynamic variables. See also User parameters.

nkey: int, "0"

The number of key frames allocated in mjModel is the larger of this value and the number of key elements below. Note that the interactive simulator has the ability to take snapshots of the system state and save them as key frames.

nuser_body: int, "-1"

The number of custom user parameters added to the definition of each body. See also User parameters. The parameter values are set via the user attribute of the body element. These values are not accessed by MuJoCo. They can be used to define element properties needed in user callbacks and other custom code.

nuser_jnt: int, "-1"

The number of custom user parameters added to the definition of each joint.

nuser_geom: int, "-1"

The number of custom user parameters added to the definition of each geom.

nuser_site: int, "-1"

The number of custom user parameters added to the definition of each site.

nuser_cam: int, "-1"

The number of custom user parameters added to the definition of each camera.

nuser_tendon: int, "-1"

The number of custom user parameters added to the definition of each tendon.

nuser_actuator: int, "-1"

The number of custom user parameters added to the definition of each actuator.

nuser_sensor: int, "-1"

The number of custom user parameters added to the definition of each sensor.

visual (*)

This element is in one-to-one correspondence with the low level structure mjVisual contained in the field mjModel.vis of mjModel. The settings here affect the visualizer, or more precisely the abstract phase of visualization which yields a list of geometric entities for subsequent rendering. The settings here are global, in contrast with the element-specific visual settings. The global and element-specific settings refer to non-overlapping properties. Some of the global settings affect properties such as triangulation of geometric primitives that cannot be set per element. Other global settings affect the properties of decorative objects, i.e., objects such as contact points and force arrows which do not correspond to model elements. The visual settings are grouped semantically into several subsections.
This element is a good candidate for the file include mechanism. One can create an XML file with coordinated visual settings corresponding to a "theme", and then include this file in multiple models.

visual/ global (?)

While all settings in mjVisual are global, the settings here could not be fit into any of the other subsections. So this is effectively a miscellaneous subsection.

fovy: real, "45"

This attribute specifies the vertical field of view of the free camera, i.e., the camera that is always available in the visualizer even if no cameras are explicitly defined in the model. It is always expressed in degrees, regardless of the setting of the angle attribute of compiler, and is also represented in the low level model in degrees. This is because we pass it to OpenGL which uses degrees. The same convention applies to the fovy attribute of the camera element below.

ipd: real, "0.068"

This attribute specifies the inter-pupilary distance of the free camera. It only affects the rendering in stereoscopic mode. The left and right viewpoints are offset by half of this value in the corresponding direction.

azimuth: real, "90"

This attribute specifies the initial azimuth of the free camera around the vertical z-axis, in degrees. A value of 0 corresponds to looking in the positive x direction, while the default value of 90 corresponds to looking in the positive y direction.

elevation: real, "-45"

This attribute specifies the initial elevation of the free camera with respect to the lookat point. Note that since this is a rotation around a vector parallel to the camera's X-axis (right in pixel space), *negative* numbers correspond to moving the camera *up* from the horizontal plane, and vice-versa.

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linewidth: real, "1"

This attribute specifies the line-width in the sense of OpenGL. It affects the rendering in wire-frame mode.

glow: real, "0.3"

The value of this attribute is added to the emission coefficient of all geoms attached to the selected body. As a result, the selected body appears to glow.

realtime: real, "1"

This value sets the initial real-time factor of the model, when loaded in *simulate*. 1: real time. Less than 1: slower than real time. Must be greater than 0.

offwidth: int, "640"

This and the next attribute specify the size in pixels of the off-screen OpenGL rendering buffer. This attribute specifies the width of the buffer. The size of this buffer can also be adjusted at runtime, but it is usually more convenient to set it in the XML.

offheight: int, "480"

This attribute specifies the height in pixels of the OpenGL off-screen rendering buffer.

visual/ quality (?)

This element specifies settings that affect the quality of the rendering. Larger values result in higher quality but possibly slower speed. Note that simulate.cc displays the frames per second (FPS). The target FPS is 60 Hz; if the number shown in the visualizer is substantially lower, this means that the GPU is over-loaded and the visualization should somehow be simplified.

shadowsize: int, "4096"

This attribute specifies the size of the square texture used for shadow mapping. Higher values result is smoother shadows. The size of the area over which a light can cast shadows also affects smoothness, so these settings should be adjusted jointly. The default here is somewhat conservative. Most modern GPUs are able to handle significantly larger textures without slowing down.

offsamples: int, "4"

This attribute specifies the number of multi-samples for offscreen rendering. Larger values produce better anti-aliasing but can slow down the GPU. Set this to 0 to disable multi-sampling. Note that this attribute only affects offscreen rendering. For regular window rendering, multi-sampling is specified in an OS-dependent way when the OpenGL context for the window is first created, and cannot be changed from within MuJoCo.

numslices: int, "28"

This and the next three attributes specify the density of internally-generated meshes for geometric primitives. Such meshes are only used for rendering, while the collision detector works with the underlying analytic surfaces. This value is passed to the various visualizer functions as the "slices" parameter as used in GLU. It specifies the number of subdivisions around the Z-axis, similar to lines of longitude.

numstacks: int, "16"

This value of this attribute is passed to the various visualization functions as the "stacks" parameter as used in GLU. It specifies the number of subdivisions along the Z-axis, similar to lines of latitude.

numquads: int, "4"

This attribute specifies the number of rectangles for rendering box faces, automatically-generated planes (as opposed to geom planes which have an element-specific attribute with the same function), and sides of height fields. Even though a geometrically correct rendering can be obtained by setting this value to 1, illumination works better for larger values because we use per-vertex illumination (as opposed to per-fragment).

visual/ headlight (?)

This element is used to adjust the properties of the headlight. There is always a built-in headlight, in addition to any lights explicitly defined in the model. The headlight is a directional light centered at the current camera and pointed in the direction in which the camera is looking. It does not cast shadows (which would be invisible anyway). Note that lights are additive, so if explicit lights are defined in the model, the intensity of the headlight would normally need to be reduced.

ambient: real(3), "0.1 0.1 0.1"

The ambient component of the headlight, in the sense of OpenGL. The alpha component here and in the next two attributes is set to 1 and cannot be adjusted.

diffuse: real(3), "0.4 0.4 0.4"

The diffuse component of the headlight, in the sense of OpenGL.

specular: real(3), "0.5 0.5 0.5"

The specular component of the headlight, in the sense of OpenGL.

active: int, "1"

This attribute enables and disables the headlight. A value of 0 means disabled, any other value means enabled.

visual/ map (?)

This element is used to specify scaling quantities that affect both the visualization and built-in mouse perturbations. Unlike the scaling quantities in the next element which are specific to spatial extent, the quantities here are miscellaneous.

stiffness: real, "100"

This attribute controls the strength of mouse perturbations. The internal perturbation mechanism simulates a mass-spring-damper with critical damping, unit mass, and stiffness given here. Larger values mean that a larger force will be applied for the same displacement between the selected body and the mouse-controlled target.

stiffnessrot: real, "500"

Same as above but applies to rotational perturbations rather than translational perturbations. Empirically, the rotati ↑ Back to top needs to be larger in order for rotational mouse perturbations to have an effect.

force: real, "0.005"

This attributes controls the visualization of both contact forces and perturbation forces. The length of the rendered force vector equals the force magnitude multiplied by the value of this attribute and divided by the mean body mass for the model (see statistic element below).

torque: real, "0.1"

Same as above, but controls the rendering of contact torque and perturbation torque rather than force (currently disabled).

alpha: real, "0.3"

When transparency is turned on in the visualizer, the geoms attached to all moving bodies are made more transparent. This is done by multiplying the geom-specific alpha values by this value.

fogstart: real, "3"

The visualizer can simulate linear fog, in the sense of OpenGL. The start position of the fog is the model extent (see statistic element below) multiplied by the value of this attribute.

fogend: real, "10"

The end position of the fog is the model extent multiplied by the value of this attribute.

znear: real, "0.01"

This and the next attribute determine the clipping planes of the OpenGL projection. The near clipping plane is particularly important: setting it too close causes (often severe) loss of resolution in the depth buffer, while setting it too far causes objects of interest to be clipped, making it impossible to zoom in. The distance to the near clipping plane is the model extent multiplied by the value of this attribute. Must be strictly positive.

zfar: real, "50"

The distance to the far clipping plane is the model extent multiplied by the value of this attribute.

haze: real, "0.3"

Proportion of the distance-to-horizon that is covered by haze (when haze rendering is enabled and a skybox is present).

shadowclip: real, "1"

As mentioned above, shadow quality depends on the size of the shadow texture as well as the area where a given light can cast shadows. For directional lights, the area would be infinite unless we limited it somehow. This attribute specifies the limits, as +/- the model extent multiplied by the present value. These limits define a square in the plane orthogonal to the light direction. If a shadow crosses the boundary of this virtual square, it will disappear abruptly, revealing the edges of the square.

shadowscale: real, "0.6"

This attribute plays a similar role as the previous one, but applies to spotlights rather than directional lights. Spotlights have a cutoff angle, limited internally to 80 deg. However this angle is often too large to obtain good quality shadows, and it is necessary to limit the shadow to a smaller cone. The angle of the cone in which shadows can be cast is the light cutoff multiplied by the present value.

actuatortendon: real, "2"

Ratio of actuator width to tendon width for rendering of actuators attached to tendons.

visual/ scale (?)

The settings in this element control the spatial extent of various decorative objects. In all cases, the rendered size equals the mean body size (see statistic element below) multiplied by the value of an attribute documented below.

forcewidth: real, "0.1"

The radius of the arrows used to render contact forces and perturbation forces.

contactwidth: real, "0.3"

The radius of the cylinders used to render contact points. The normal direction of the cylinder is aligned with the contact normal. Making the cylinder short and wide results in a "pancake" representation of the tangent plane.

contactheight: real, "0.1"

The height of the cylinders used to render contact points.

connect: real, "0.2"

The radius of the capsules used to connect bodies and joints, resulting in an automatically generated skeleton.

com: real, "0.4"

The radius of the spheres used to render the centers of mass of kinematic sub-trees.

camera: real, "0.3"

The size of the decorative object used to represent model cameras in the rendering.

light: real, "0.3"

The size of the decorative object used to represent model lights in the rendering.

selectpoint: real, "0.2"

The radius of the sphere used to render the selection point (i.e., the point where the user left-double-clicked to select a body). Note that the local and global coordinates of this point can be printed in the 3D view by activating the corresponding rendering flags. In this way, the coordinates of points of interest can be found.

jointlength: real, "1.0"

The length of the arrows used to render joint axes.

jointwidth: real, "0.1"

The radius of the arrows used to render joint axes.

actuatorlength: real, “0.7”

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The length of the arro nder actuators acting on scalar joints only.

actuatorwidth: real, “0.2”

The radius of the arrows used to render actuators acting on scalar joints only.

framelength: real, “1.0”

The length of the cylinders used to render coordinate frames. The world frame is automatically scaled relative to this setting.

framewidth: real, “0.1”

The radius of the cylinders used to render coordinate frames.

constraint: real, “0.1”

The radius of the capsules used to render violations in spatial constraints.

slidercrank: real, “0.2”

The radius of the capsules used to render slider-crank mechanisms. The second part of the mechanism is automatically scaled relative to this setting.

visual/ rgba (?)

The settings in this element control the color and transparency (rgba) of various decorative objects. We will call this combined attribute “color” to simplify terminology below. All values should be in the range [0 1]. An alpha value of 0 disables the rendering of the corresponding object.

fog: real(4), “0 0 0 1”

When fog is enabled, the color of all pixels fades towards the color specified here. The spatial extent of the fading is controlled by the fogstart and fogend attributes of the map element above.

haze: real(4), “1 1 1 1”

Haze color at the horizon, used to transition between an infinite plane and a skybox smoothly. The default creates white haze. To create a seamless transition, make sure the skybox colors near the horizon are similar to the plane color/texture, and set the haze color somewhere in that color gamut.

force: real(4), “1 0.5 0.5 1”

Color of the arrows used to render perturbation forces.

inertia: real(4), “0.8 0.2 0.2 0.6”

Color of the boxes used to render equivalent body inertias. This is the only rgba setting that has transparency by default, because it is usually desirable to see the geoms inside the inertia box.

joint: real(4), “0.2 0.6 0.8 1”

Color of the arrows used to render joint axes.

actuator: real(4), “0.2 0.25 0.2 1”

Actuator color for neutral value of the control.

actuatornegative: real(4), “0.2 0.6 0.9 1”

Actuator color for most negative value of the control.

actuatorpositive: real(4), “0.9 0.4 0.2 1”

Actuator color for most positive value of the control.

com: real(4), “0.9 0.9 0.9 1”

Color of the spheres used to render sub-tree centers of mass.

camera: real(4), “0.6 0.9 0.6 1”

Color of the decorative object used to represent model cameras in the rendering.

light: real(4), “0.6 0.6 0.9 1”

Color of the decorative object used to represent model lights in the rendering.

selectpoint: real(4), “0.9 0.9 0.1 1”

Color of the sphere used to render the selection point.

connect: real(4), “0.2 0.2 0.8 1”

Color of the capsules used to connect bodies and joints, resulting in an automatically generated skeleton.

contactpoint: real(4), “0.9 0.6 0.2 1”

Color of the cylinders used to render contact points.

contactforce: real(4), “0.7 0.9 0.9 1”

Color of the arrows used to render contact forces. When splitting of contact forces into normal and tangential components is enabled, this color is used to render the normal components.

contactfriction: real(4), “0.9 0.8 0.4 1”

Color of the arrows used to render contact tangential forces, only when splitting is enabled.

contacttorque: real(4), “0.9 0.7 0.9 1”

Color of the arrows used to render contact torques (currently disabled).

contactgap: real(4), “0.5, 0.8, 0.9, 1”

Color of contacts that fall in the contact gap (and are thereby excluded from contact force computations).

rangefinder: real(4), “1 1 0.1 1”

Color of line geoms used to render rangefinder sensors.

constraint: real(4), “0.9 0 0 1”

Color of the capsules corresponding to spatial constraint violations.

slidercrank: real(4), “0.5 0.3 0.8 1”

Color of slider-crank mechanisms.

crankbroken: real(4), “0.9 0 0 1”

Color used to render the crank of slide-crank mechanisms, in model configurations where the specified rod length ↑ Back to top ntained, i.e., it is “broken”.

statistic (*)

This element is used to override model statistics computed by the compiler. These statistics are not only informational but are also used to scale various components of the rendering and perturbation. We provide an override mechanism in the XML because it is sometimes easier to adjust a small number of model statistics than a larger number of visual parameters.

meanmass: real, optional

If this attribute is specified, it replaces the value of mjModel.stat.meanmass computed by the compiler. The computed value is the average body mass, not counting the massless world body. At runtime this value scales the perturbation force.

meaninertia: real, optional

If this attribute is specified, it replaces the value of mjModel.stat.meaninertia computed by the compiler. The computed value is the average diagonal element of the joint-space inertia matrix when the model is in qpos0. At runtime this value scales the solver cost and gradient used for early termination.

meansize: real, optional

If this attribute is specified, it replaces the value of `mjModel.stat.meansize` computed by the compiler. At runtime this value multiplies the attributes of the scale element above, and acts as their length unit. If specific lengths are desired, it can be convenient to set meansize to a round number like 1 or 0.01 so that scale values are in recognized length units. This is the only semantic of meansize and setting it has no other side-effect. The automatically computed value is heuristic, representing the average body radius. The heuristic is based on geom sizes when present, the distances between joints when present, and the sizes of the body equivalent inertia boxes.

extent: real, optional

If this attribute is specified, it replaces the value of mjModel.stat.extent computed by the compiler. The computed value is half the side of the bounding box of the model in the initial configuration. At runtime this value is multiplied by some of the attributes of the map element above. When the model is first loaded, the free camera’s initial distance from the center (see below) is 1.5 times the extent. Must be strictly positive.

center: real(3), optional

If this attribute is specified, it replaces the value of mjModel.stat.center computed by the compiler. The computed value is the center of the bounding box of the entire model in the initial configuration. This 3D vector is used to center the view of the free camera when the model is first loaded.

default (R)

This element is used to create a new defaults class; see Default settings above. Defaults classes can be nested, inheriting all attribute values from their parent. The top-level defaults class is always defined; it is called “main” if omitted.

class: string, required (except at the top level)

The name of the defaults class. It must be unique among all defaults classes. This name is used to make the class active when creating an actual model element.

default/ mesh (?)

This element sets the attributes of the dummy mesh element of the defaults class.
The only mesh attribute available here is: **scale**.

default/ material (?)

This element sets the attributes of the dummy material element of the defaults class.
All material attributes are available here except: name, class.

default/ joint (?)

This element sets the attributes of the dummy joint element of the defaults class.
All joint attributes are available here except: name, class.

default/ geom (?)

This element sets the attributes of the dummy geom element of the defaults class.
All geom attributes are available here except: name, class.

default/ site (?)

This element sets the attributes of the dummy site element of the defaults class.
All site attributes are available here except: name, class.

default/ camera (?)

This element sets the attributes of the dummy camera element of the defaults class.
All camera attributes are available here except: name, class.

default/ light (?)

This element sets the attributes of the dummy light element of the defaults class.
All light attributes are available here except: name, class.

default/ pair (?)

This element sets the attributes of the dummy pair element of the defaults class.
All pair attributes are available here except: name, class, geom1, geom2.

default/ equality (?)

This element sets the attributes of the dummy equality element of the defaults class. The actual equality constraints have types depending on the sub-element used to define them. However here we are setting attributes common to all equality constraint types, which is why we do not make a distinction between types.
The equality sub-element attributes available here are: **active, solref, solimp**.

default/ tendon (?)

This element sets the attributes of the dummy tendon element of the defaults class. Similar to equality constraints, the ac ↑ Back to top have types, but here we are setting attributes common to all types.
All tendon sub-element attributes are available here except: name, class.

default/ general (?)

This element sets the attributes of the dummy general element of the defaults class.
All general attributes are available here except: name, class, joint, jointinparent, site, tendon, slidersite, cranksite.

default/ motor (?)

This and the next three elements set the attributes of the general element using Actuator shortcuts. It does not make sense to use more than one such shortcut in the same defaults class, because they set the same underlying attributes, replacing any previous settings. All motor attributes are available here except: name, class, joint, jointinparent, site, tendon, slidersite, cranksite.

default/ position (?)

All position attributes are available here except: name, class, joint, jointinparent, site, tendon, slidersite, cranksite.

default/ velocity (?)

All velocity attributes are available here except: name, class, joint, jointinparent, site, tendon, slidersite, cranksite.

default/ intvelocity (?)

All intvelocity attributes are available here except: name, class, joint, jointinparent, site, tendon, slidersite, cranksite.

default/ damper (?)

All damper attributes are available here except: name, class, joint, jointinparent, site, tendon, slidersite, cranksite.

default/ cylinder (?)

All cylinder attributes are available here except: name, class, joint, jointinparent, site, tendon, slidersite, cranksite.

default/ muscle (?)

All muscle attributes are available here except: name, class, joint, jointinparent, site, tendon, slidersite, cranksite.

default/ adhesion (?)

All adhesion attributes are available here except: name, class, body.

custom (*)

This is a grouping element for custom numeric and text elements. It does not have attributes.

custom/ numeric (*)

This element creates a custom numeric array in mjModel.

name: string, required

> The name of the array. This attribute is required because the only way to find a custom element of interest at runtime is through its name.

size: int, optional

> If specified this attribute sets the size of the data array, in doubles. If this attribute is not specified, the size will be inferred from the actual data array below.

data: real(size), "0 0 ..."

> Numeric data to be copied into mjModel. If size is specified, the length of the array given here cannot exceed the specified size. If the length of the array is smaller, the missing components are set to 0. Note that custom arrays can be created for storing information at runtime - which is why data initialization is optional. It becomes required only when the array size is omitted.

custom/ text (*)

This element creates a custom text field in mjModel. It could be used to store keyword commands for user callbacks and other custom computations.

name: string, required

> Name of the custom text field.

data: string, required

> Custom text to be copied into mjModel.

custom/ tuple (*)

This element creates a custom tuple, which is a list of MuJoCo objects. The list is created by referencing the desired objects by name.

name: string, required

> Name of the custom tuple.

custom/tuple/ element (*)

This adds an element to the tuple.

objtype: (any element type that can be named), required

> Type of the object being added.

objname: string, required

> Name of the object being added. The type and name must reference a named MuJoCo element defined somewhere in the model. Tuples can also be referenced (including self-references).

prm: real, "0"

> Real-valued parameter associated with this element of the tuple. Its use is up to the user.

asset (*)

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This is a grouping element for defining assets. It does not have attributes. Assets are created in the model so that they can be referenced from other model elements; recall the discussion of Assets in the Overview chapter.

asset/ texture (*)

This element creates a texture asset, which is then referenced from a material asset, which is finally referenced from a model element that needs to be textured. MuJoCo provides access to the texture mapping mechanism in OpenGL. Texture coordinates are generated automatically in GL_OBJECT_PLANE mode, using either 2D or cube mapping. MIP maps are always enabled in GL_LINEAR_MIPMAP_LINEAR mode. The texture color is combined with the object color in GL_MODULATE mode. The texture data can be loaded from PNG files, with provisions for loading cube and skybox textures. Alternatively the data can be generated by the compiler as a procedural texture. Because different texture types require different parameters, only a subset of the attributes below are used for any given texture.
MuJoCo 2.0 introduced a second file format for loading textures, in addition to PNG. If the file name extension is different from .png or .PNG, MuJoCo assumes that the texture is in the new format. This is a custom binary file format, containing the following data:

```
(int32)   width
(int32)   height
(byte)    rgb_data[3*width*height]
```

name: string, optional

As with all other assets, a texture must have a name in order to be referenced. However if the texture is loaded from a single file with the file attribute, the explicit name can be omitted and the file name (without the path and extension) becomes the texture name. If the name after parsing is empty and the texture type is not "skybox", the compiler will generate an error.

type: [2d, cube, skybox], "cube"

This attribute determines how the texture is represented and mapped to objects. It also determines which of the remaining attributes are relevant. The keywords have the following meaning:

The **cube** type is the most common. It has the effect of shrink-wrapping a texture cube over an object. Apart from the adjustment provided by the texuniform attribute of material, the process is automatic. Internally the GPU constructs a ray from the center of the object to each pixel (or rather fragment), finds the intersection of this ray with the cube surface (the cube and the object have the same center), and uses the corresponding texture color. The six square images defining the cube can be the same or different; if they are the same, only one copy is stored in mjModel. There are four mechanisms for specifying the texture data:

1. Single file (PNG or custom) specified with the file attribute, containing a square image which is repeated on each side of the cube. This is the most common approach. If for example the goal is to create the appearance of wood, repeating the same image on all sides is sufficient.
2. Single file containing a composite image from which the six squares are extracted by the compiler. The layout of the composite image is determined by the gridsize and gridlayout attributes.
3. Six separate files specified with the attributes fileright, fileleft etc, each containing one square image.
4. Procedural texture generated internally. The type of procedural texture is determined by the builtin attribute. The texture data also depends on a number of parameters documented below.

The **skybox** type is very similar to cube mapping, and in fact the texture data is specified in exactly the same way. The only difference is that the visualizer uses the first such texture defined in the model to render a skybox. This is a large box centered at the camera and always moving with it, with size determined automatically from the far clipping plane. The idea is that images on the skybox appear stationary, as if they are infinitely far away. If such a texture is referenced from a material applied to a regular object, the effect is equivalent to a cube map. Note however that the images suitable for skyboxes are rarely suitable for texturing objects.

The **2d** type may be the most familiar to users, however it is only suitable for planes and height fields. This is because the texture coordinate generator is trying to map a 2D image to 3D space, and as a result there are entire curves on the object surface that correspond to the same texture pixel. For a box geom for example, the two faces whose normals are aligned with the Z axis of the local frame appear normal, while the other four faces appear stretched. For planes this is not an issue because the plane is always normal to the local Z axis. For height fields the sides enclosing the terrain map appear stretched, but in that case the effect is actually desirable. 2d textures can be rectangular, unlike the sides of cube textures which must be square. The scaling can be controlled with the texrepeat attribute of material. The data can be loaded from a singlefile or created procedurally.

file: string, optional

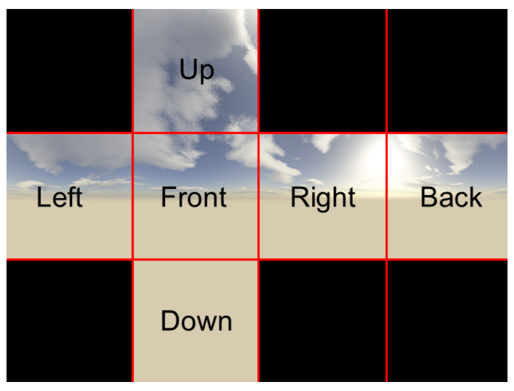
If this attribute is specified, and the builtin attribute below is set to "none", the texture data is loaded from a single file. See the texturedir attribute of compiler regarding the file path.

gridsize: int(2), "1 1"

When a cube or skybox texture is loaded from a single file, this attribute and the next specify how the six square sides of the texture cube are obtained from the single image. The default setting "1 1" means that the same image is repeated on all sides of the cube. Otherwise the image is interpreted as a grid from which the six sides are extracted. The two integers here correspond to the number of rows and columns in the grid. Each integer must be positive and the product of the two cannot exceed 12. The number of rows and columns in the image must be integer multiples of the number of rows and columns in the grid, and these two multiples must be equal, so that the extracted images are square.

gridlayout: string, "............"

When a cube or skybox texture is loaded from a single file, and the grid size is different from "1 1", this attribute specifies which grid cells are used and which side of the cube they correspond to. There are many skybox textures available online as composite images, but they



do not use the same convention, which is why we have designed a flexible m decoding them. The string specified here must be composed of characters from the set {'.', 'R', 'L', 'U', 'D', 'F', 'B'}. The number of characters must equal the product of the two grid sizes. The grid is scanned in row-major order. The '.' character denotes an unused cell. The other characters are the first letters of Right, Left, Up, Down, Front, Back; see below for coordinate frame description. If the symbol for a given side appears more than once, the last definition is used. If a given side is omitted, it is filled with the color specified by the rgb1 attribute. For example, the desert landscape below can be loaded as a skybox or a cube map using gridsize = "3 4" and gridlayout = ".U..LFRB.D.." The full-resolution image file without the markings can be downloaded here.

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fileright, **fileleft**, **fileup**, **filedown**, **filefront**, **fileback** : string, optional

These attributes are used to load the six sides of a cube or skybox texture from separate files, but only if the file attribute is omitted and the builtin attribute is set to "none". If any one of these attributes are omitted, the corresponding side is filled with the color specified by the rgb1 attribute. The coordinate frame here is unusual. When a skybox is viewed with the default free camera in its initial configuration, the Right, Left, Up, Down sides appear where one would expect them. The Back side appears in front of the viewer, because the viewer is in the middle of the box and is facing its back. There is however a complication. In MuJoCo the +Z axis points up, while existing skybox textures (which are non-trivial to design) tend to assume that the +Y axis points up. Changing coordinates cannot be done by merely renaming files; instead one would have to transpose and/or mirror some of the images. To avoid this complication, we render the skybox rotated by 90 deg around the +X axis, in violation of our convention. However we cannot do the same for regular objects. Thus the mapping of skybox and cube textures on regular objects, expressed in the local frame of the object, is as follows: Right = +X, Left = -X, Up = +Y, Down = -Y, Front = +Z, Back = -Z.

builtin: [none, gradient, checker, flat], "none"

This and the remaining attributes control the generation of procedural textures. If the value of this attribute is different from "none", the texture is treated as procedural and any file names are ignored. The keywords have the following meaning: The **gradient** type generates a color gradient from rgb1 to rgb2. The interpolation in color space is done through a sigmoid function. For cube and skybox textures the gradient is along the +Y axis, i.e., from top to bottom for skybox rendering.

The **checker** type generates a 2-by-2 checker pattern with alternating colors given by rgb1 to rgb2. This is suitable for rendering ground planes and also for marking objects with rotational symmetries. Note that 2d textures can be scaled so as to repeat the pattern as many times as necessary. For cube and skybox textures, the checker pattern is painted on each side of the cube.

The **flat** type fills the entire texture with rgb1, except for the bottom face of cube and skybox textures which is filled with rgb2.

rgb1: real(3), "0.8 0.8 0.8"

The first color used for procedural texture generation. This color is also used to fill missing sides of cube and skybox textures loaded from files. The components of this and all other RGB(A) vectors should be in the range [0 1].

rgb2: real(3), "0.5 0.5 0.5"

The second color used for procedural texture generation.

mark: [none, edge, cross, random], "none"

Procedural textures can be marked with the markrgb color, on top of the colors determined by the builtin type. "edge" means that the edges of all texture images are marked. "cross" means that a cross is marked in the middle of each image. "random" means that randomly chosen pixels are marked. All markings are one-pixel wide, thus the markings appear larger and more diffuse on smaller textures.

markrgb: real(3), "0 0 0"

The color used for procedural texture markings.

random: real, "0.01"

When the mark attribute is set to "random", this attribute determines the probability of turning on each pixel. Note that larger textures have more pixels, and the probability here is applied independently to each pixel - thus the texture size and probability need to be adjusted jointly. Together with a gradient skybox texture, this can create the appearance of a night sky with stars.

width: int, "0"

The width of the procedural texture, i.e., the number of columns in the image. For cube and skybox procedural textures the width and height must be equal. Larger values usually result in higher quality images, although in some cases (e.g. checker patterns) small values are sufficient.

height: int, "0"

The height of the procedural texture, i.e., the number of rows in the image.

hflip: [false, true], "false"

If true, images loaded from file are flipped in the horizontal direction. Does not affect procedural textures.

vflip: [false, true], "false"

If true, images loaded from file are flipped in the vertical direction. Does not affect procedural textures.

asset/ hfield (*)

This element creates a height field asset, which can then be referenced from geoms with type "hfield". A height field, also known as terrain map, is a 2D matrix of elevation data. The data can be specified in one of three ways:

1. The elevation data can be loaded from a PNG file. The image is converted internally to gray scale, and the intensity of each pixel is used to define elevation; white is high and black is low.

2. The elevation data can be loaded from a binary file in the custom format described below. As with all other matrices u ↑ Back to top o, the data ordering is row-major, like pixels in an image. If the data size is nrow-by-ncol, the file must have 4*(2+nrow*ncol) bytes:

   ```
   (int32)   nrow
   (int32)   ncol
   (float32) data[nrow*ncol]
   ```

3. The elevation data can be left undefined at compile time. This is done by specifying the attributes nrow and ncol. The compiler allocates space for the height field data in mjModel and sets it to 0. The user can then generate a custom height field at runtime, either programmatically or using sensor data.

Regardless of which method is used to specify the elevation data, the compiler always normalizes it to the range [0 1]. However if the data is left undefined at compile time and generated later at runtime, it is the user's responsibility to normalize it.
The position and orientation of the height field is determined by the geom that references it. The spatial extent on the other hand is specified by the height field asset itself via the size attribute, and cannot be modified by the referencing geom (the geom size parameters are ignored in this case). The same approach is used for meshes below: positioning is done by the geom while sizing is done by the asset. This is because height fields and meshes involve sizing operations that are not common to other geoms.
For collision detection, a height field is treated as a union of triangular prisms. Collisions between height fields and other geoms (except for planes and other height fields which are not supported) are computed by first selecting the sub-grid of prisms that could collide with the geom based on its bounding box, and then using the general convex collider. The number of possible contacts between a height field and a geom is limited to 9; any contacts beyond that are discarded. To avoid penetration due to discarded contacts, the spatial features of the height field should be large compared to the geoms it collides with.

name: string, optional

Name of the height field, used for referencing. If the name is omitted and a file name is specified, the height field name equals the file name without the path and extension.

file: string, optional

If this attribute is specified, the elevation data is loaded from the given file. If the file extension is ".png", not case-sensitive, the file is treated as a PNG file. Otherwise it is treated as a binary file in the above custom format. The number of rows and columns in the data are determined from the file contents. Loading data from a file and setting nrow or ncol below to non-zero values results is compile error, even if these settings are consistent with the file contents.

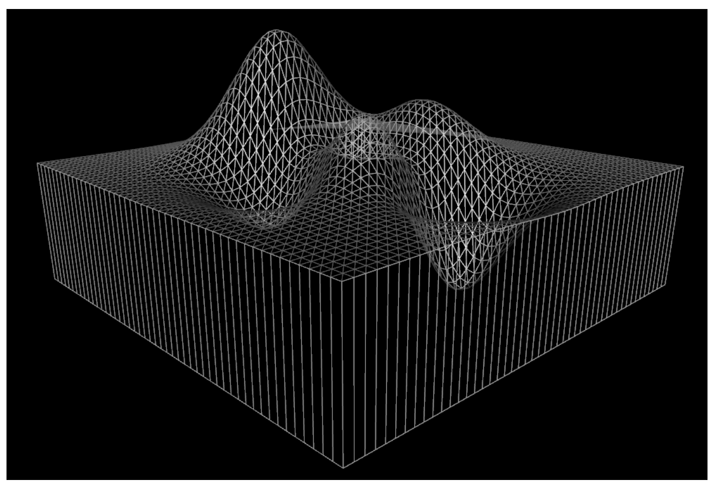
nrow: int, "0"

This attribute and the next are used to allocate a height field in mjModel and leave the elevation data undefined (i.e., set to 0). This attribute specifies the number of rows in the elevation data matrix. The default value of 0 means that the data will be loaded from a file, which will be used to infer the size of the matrix.

ncol: int, "0"

This attribute specifies the number of columns in the elevation data matrix.

size: real(4), required



The four numbers here are (radius_x, radius_y, elevation_z, base_z). The height field is centered at the referencing geom's local frame. Elevation is in the +Z direction. The first two numbers specify the X and Y extent (or "radius") of the rectangle over which the height field is defined. This may seem unnatural for rectangles, but it is natural for spheres and other geom types, and we prefer to use the same convention throughout the model. The third number is the maximum elevation; it scales the elevation data which is normalized to [0-1]. Thus the minimum elevation point is at Z=0 and the maximum elevation point is at Z=elevation_z. The last number is the depth of a box in the -Z direction serving as a "base" for the height field. Without this automatically generated box, the height field would have zero thickness at places there the normalized elevation data is zero. Unlike planes which impose global unilateral constraints, height fields are treated as unions of regular geoms, so there is no notion of being "under" the height field. Instead a geom is either inside or outside the height field - which is why the inside part must have non-zero thickness. The example on the right is the MATLAB "peaks" surface saved in our custom height field format, and loaded as an asset with size = "1 1 1 0.1". The horizontal size of the box is 2, the difference between the maximum and minimum elevation is 1, and the depth of the base added below the minimum elevation point is 0.1.

asset/ mesh (*)

This element creates a mesh asset, which can then be referenced from geoms. If the referencing geom type is mesh the mesh is instantiated in the model, otherwise a geometric primitive is automatically fitted to it; see the geom element below.

MuJoCo works with triangulated meshes. They can be loaded from binary STL files, OBJ files or MSH files with custom format described below, or vertex and face data specified directly in the XML. Software such as MeshLab can be used to convert from other mesh formats to STL or OBJ. While any collection of triangles can be loaded as a mesh and rendered, collision detection works with the convex hull of the mesh as explained in Collision detection. See also the convexhull attribute of the compiler element which controls the automatic generation of convex hulls. The mesh appearance (including texture mapping) is controlled by the material and rgba attributes of the referencing geom, similarly to height fields.

Starting with MuJoCo 2.0, meshes can have explicit texture coordinates instead of relying on the automated texture mapping mechanism. When provided, these explicit coordinates have priority. Note that texture coordinates can be specified with OBJ files and MSH files, as well as explicitly in the XML with the texcoord attribute, but not via STL files. These mechanism cannot be mixed. So if you have an STL mesh, the only way to add texture coordinates to it is to convert to one of the other supported formats.

MSH file format

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The binary MSH file s[illegible]egers specifying the number of vertex positions (nvertex), vertex normals (nnormal), vertex texture coordinates (ntexcoord), and vertex indices making up the faces (nface), followed by the numeric data. nvertex must be at least 4. nnormal and ntexcoord can be zero (in which case the corresponding data is not defined) or equal to nvertex. nface can also be zero, in which case faces are constructed automatically from the convex hull of the vertex positions. The file size in bytes must be exactly: 16 + 12*(nvertex + nnormal + nface) + 8*ntexcoord. The contents of the file must be as follows:

```
(int32)   nvertex
(int32)   nnormal
(int32)   ntexcoord
(int32)   nface
(float)   vertex_positions[3*nvertex]
(float)   vertex_normals[3*nnormal]
(float)   vertex_texcoords[2*ntexcoord]
(int32)   face_vertex_indices[3*nface]
```

Poorly designed meshes can display rendering artifacts. In particular, the shadow mapping mechanism relies on having some distance between front and back-facing triangle faces. If the faces are repeated, with opposite normals as determined by the vertex order in each triangle, this causes shadow aliasing. The solution is to remove the repeated faces (which can be done in MeshLab) or use a better designed mesh. Flipped faces are checked by MuJoCo for meshes specified as OBJ or XML and an error message is returned.

The size of the mesh is determined by the 3D coordinates of the vertex data in the mesh file, multiplied by the components of the scale attribute below. Scaling is applied separately for each coordinate axis. Note that negative scaling values can be used to flip the mesh; this is a legitimate operation. The size parameters of the referening geoms are ignored, similarly to height fields. As of MuJoCo 2.0 we also provide a mechanism to translate and rotate the 3D coordinates, using the attributes refpos and refquat.

Another new feature in MuJoCo 2.0 is that a mesh can be defined without faces (a point cloud essentially). In that case the convex hull is constructed automatically, even if the compiler attribute convexhull is false. This makes it easy to construct simple shapes directly in the XML. For example, a pyramid can be created as:

```
<asset>
    <mesh name="pyramid" vertex="0 0 0  1 0 0  0 1 0  0 0 1"/>
</asset>
```

Positioning and orienting is complicated by the fact that vertex data are often designed relative to coordinate frames whose origin is not inside the mesh. In contrast, MuJoCo expects the origin of a geom's local frame to coincide with the geometric center of the shape. We resolve this discrepancy by pre-processing the mesh in the compiler, so that it is centered around (0,0,0) and its principal axes of inertia are the coordinate axes. We also save the translation and rotation offsets needed to achieve such alignment. These offsets are then applied to the referencing geom's position and orientation; see also mesh attribute of geom below. Fortunately most meshes used in robot models are designed in a coordinate frame centered at the joint. This makes the corresponding MJCF model intuitive: we set the body frame at the joint, so that the joint position is (0,0,0) in the body frame, and simply reference the mesh. Below is an MJCF model fragment of a forearm, containing all the information needed to put the mesh where one would expect it to be. The body position is specified relative to the parent body, namely the upper arm (not shown). It is offset by 35 cm which is the typical length of the human upper arm. If the mesh vertex data were not designed in the above convention, we would have to use the geom position and orientation (or the new refpos, refquat mechanism) to compensate, but in practice this is rarely needed.

```
<asset>
    <mesh file="forearm.stl"/>
</asset>

<body pos="0 0 0.35"/>
    <joint type="hinge" axis="1 0 0"/>
    <geom type="mesh" mesh="forearm"/>
</body>
```

The inertial computation mentioned above is part of an algorithm used not only to center and align the mesh, but also to infer the mass and inertia of the body to which it is attached. This is done by computing the centroid of the triangle faces, connecting each face with the centroid to form a triangular pyramid, computing the mass and signed inertia of all pyramids (considered solid or hollow if shellinertia is true) and accumulating them. The sign ensures that pyramids on the outside of the surfaces are subtracted, as it can occur with concave geometries. This algorithm can be found in section 1.3.8 of Computational Geometry in C (Second Edition) by Joseph O'Rourke.

The full list of processing steps applied by the compiler to each mesh is as follows:

1. For STL meshes, remove any repeated vertices and re-index the faces if needed. If the mesh is not STL, we assume that the desired vertices and faces have already been generated and do not apply removal or re-indexing;
2. If vertex normals are not provided, generate normals automatically, using a weighted average of the surrounding face normals. If sharp edges are encountered, the renderer uses the face normals to preserve the visual information about the edge, unless smoothnormal is true. Note that normals cannot be provided with STL meshes;
3. Scale, translate and rotate the vertices and normals, re-normalize the normals in case of scaling;
4. Construct the convex hull if specified;
5. Find the centroid of all triangle faces, and construct the union-of-pyramids representation. Triangles whose area is too small (below the mjMINVAL value of 1E-14) result in compile error;
6. Compute the center of mass and inertia matrix of the union-of-pyramids. Use eigenvalue decomposition to find the principal axes of inertia. Center and align the mesh, saving the translational and rotational offsets for subsequent geom-related computations.

name: string, optional

Name of the mesh, used for referencing. If omitted, the mesh name equals the file name without the path and extension.

class: string, optional

Defaults class for setting unspecified attributes (only scale in this case).

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file: string, optional

The file from which the mesh will be loaded. The path is determined as described in the meshdir attribute of compiler. The file extension must be “stl” or “msh” (not case sensitive) specifying the file type. If the file name is omitted, the vertex attribute becomes required.

scale: real(3), “1 1 1”

This attribute specifies the scaling that will be applied to the vertex data along each coordinate axis. Negative values are allowed, resulting in flipping the mesh along the corresponding axis.

smoothnormal: [false, true], “false”

Controls the automatic generation of vertex normals when normals are not given explicitly. If true, smooth normals are generated by averaging the face normals at each vertex, with weight proportional to the face area. If false, faces at large angles relative to the average normal are excluded from the average. In this way, sharp edges (as in cube edges) are not smoothed.

vertex: real(3*nvert), optional

Vertex 3D position data. You can specify position data in the XML using this attribute, or using a binary file, but not both.

normal: real(3*nvert), optional

Vertex 3D normal data. If specified, the number of normals must equal the number of vertices. The model compiler normalizes the normals automatically.

texcoord: real(2*nvert), optional

Vertex 2D texture coordinates, which are numbers between 0 and 1. If specified, the number of texture coordinate pairs must equal the number of vertices.

face: int(3*nface), optional

Faces of the mesh. Each face is a sequence of 3 vertex indices, in counter-clockwise order. The indices must be integers between 0 and nvert-1.

refpos: real(3), “0 0 0”

Reference position relative to which the 3D vertex coordinates are defined. This vector is subtracted from the positions.

refquat: real(4), “1 0 0 0”

Reference orientation relative to which the 3D vertex coordinates and normals are defined. The conjugate of this quaternion is used to rotate the positions and normals. The model compiler normalizes the quaternion automatically.

asset/ skin (*)

Skinned meshes (or skins) were added in MuJoCo 2.0. These are deformable meshes whose vertex positions and normals are computed each time the model is rendered. MuJoCo skins are only used for visualization and do not affect the physics in any way. In particular, collisions involve the geoms of the bodies to which the skin is attached, and not the skin itself. Unlike regular meshes which are referenced from geoms and participate in collisions, the skin is not referenced from anywhere else in the model. It is a stand-alone asset that is used by renderer and not by the simulator.

The skin has vertex positions and normals updated at runtime, and triangle faces and optional texture coordinates which are predefined. It also has “bones” used for updating. Bones are regular MuJoCo bodies referenced with the **bone** subelement. Each bone has a list of vertex indices and corresponding real-valued weights which specify how much the bone position and orientation influence the corresponding vertex. The vertex has local coordinates with respect to every bone that influences it. The local coordinates are computed by the model compiler, given global vertex coordinates and global bind poses for each body. The bind poses do not have to correspond to the model reference configuration qpos0. Note that the vertex positions and bone bind poses provided in the skin definition are always global, even if the model itself is defined in local coordinates.

At runtime the local coordinates of each vertex with respect to each bone that influences it are converted to global coordinates, and averaged in proportion to the corresponding weights to obtain a single set of 3D coordinates for each vertex. Normals then are computed automatically given the resulting global vertex positions and face information. Finally, the skin can be inflated by applying an offset to each vertex position along its (computed) normal. Skins are one-sided for rendering purposes; this is because back-face culling is needed to avoid shading and aliasing artifacts. When the skin is a closed 3D shape this does not matter because the back sides cannot be seen. But if the skin is a 2D object, we have to specify both sides and offset them slightly to avoid artifacts. Note that the composite objects introduced in MuJoCo 2.0 generate skins automatically. So one can save an XML model with a composite object, and obtain an elaborate example of how a skin is specified in the XML.

Similar to meshes, skins can be specified directly in the XML via attributes documented later, or loaded from a binary SKN file which is in a custom format. The specification of skins is more complex than meshes because of the bone subelements. The file format starts with a header of 4 integers: nvertex, ntexcoord, nface, nbone. The first three are the same as in meshes, and specify the total number of vertices, texture coordinate pairs, and triangle faces in the skin. ntexcoord can be zero or equal to nvertex. nbone specifies the number of MuJoCo bodies that will be used as bones in the skin. The header is followed by the vertex, texcoord and face data, followed by a specification for each bone. The bone specification contains the name of the corresponding model body, 3D bind position, 4D bind quaternion, number of vertices influenced by the bone, and the vertex index array and weight array. Body names are represented as fixed-length character arrays and are expected to be 0-terminated. Characters after the first 0 are ignored. The contents of the SKN file are:

```
(int32)   nvertex
(int32)   ntexcoord
(int32)   nface
(int32)   nbone
(float)   vertex_positions[3*nvertex]
(float)   vertex_texcoords[2*ntexcoord]
(int32)   face_vertex_indices[3*nface]
for each bone:
    (char)    body_name[40]
    (float)   bind_position[3]
    (float)   bind_quaternion[4]
    (int32)   vertex_count
    (int32)   vertex_index[vertex_count]
    (float)   vertex_we  ↑ Back to top  unt]
```

Similar to the other custom binary formats used in MuJoCo, the file size in bytes is strictly enforced by the model compiler. The skin file format has subelements so the overall file size formula is difficult to write down, but should be clear from the above specification.

name: string, optional

Name of the skin.

file: string, optional

The SKN file from which the skin will be loaded. The path is determined as described in the meshdir attribute of compiler. If the file is omitted, the skin specification must be provided in the XML using the attributes below.

vertex: real(3*nvert), optional

Vertex 3D positions, in the global bind pose where the skin is defined.

texcoord: real(2*nvert), optional

Vertex 2D texture coordinates, between 0 and 1. Note that skin and geom texturing are somewhat different. Geoms can use automated texture coordinate generation while skins cannot. This is because skin data are computed directly in global coordinates. So if the material references a texture, one should specify explicit texture coordinates for the skin using this attribute. Otherwise the texture will appear to be stationary in the world while the skin moves around (creating an interesting effect but probably not as intended).

face: int(3*nface), optional

Trinagular skin faces. Each face is a triple of vertex indices, which are integers between zero and nvert-1.

inflate: real, "0"

If this number is not zero, the position of vertex during updating will be offset along the vertex normal, but the distance specified in this attribute. This is particularly useful for skins representing flexible 2D shapes.

material: string, optional

If specified, this attribute applies a material to the skin.

rgba: real(4), "0.5 0.5 0.5 1"

Instead of creating material assets and referencing them, this attribute can be used to set color and transparency only. This is not as flexible as the material mechanism, but is more convenient and is often sufficient. If the value of this attribute is different from the internal default, it takes precedence over the material.

asset/skin/ bone (*)

This element defines a bone of the skin. The bone is a regular MuJoCo body which is referenced by name here.

body: string, required

Name of the body corresponding to this bone.

bindpos: real(3), required

Global body position corresponding to the bind pose.

bindquat: real(4), required

Global body orientation corresponding to the bind pose.

vertid: int(nvert), required

Integer indices of the vertices influenced by this bone. The vertex index corresponds to the order of the vertex in the skin mesh. The number of vertex indices specified here (nvert) must equal the number of vertex weights specified with the next attribute. The same vertex may be influenced by multiple bones, and each vertex must be influenced by at least one bone.

vertweight: real(nvert), required

Weights for the vertices influenced by this bone, in the same order as the vertex indices. Negative weights are allowed (which is needed for cubic interpolation for example) however the sum of all bone weights for a given vertex must be positive.

asset/ material (*)

This element creates a material asset. It can be referenced from skins, geoms, sites and tendons to set their appearance. Note that all these elements also have a local rgba attribute, which is more convenient when only colors need to be adjusted, because it does not require creating materials and referencing them. Materials are useful for adjusting appearance properties beyond color. However once a material is created, it is more natural the specify the color using the material, so that all appearance properties are grouped together.

name: string, required

Name of the material, used for referencing.

class: string, optional

Defaults class for setting unspecified attributes.

texture: string, optional

If this attribute is specified, the material has a texture associated with it. Referencing the material from a model element will cause the texture to be applied to that element. Note that the value of this attribute is the name of a texture asset, not a texture file name. Textures cannot be loaded in the material definition; instead they must be loaded explicitly via the texture element and then referenced here.

texrepeat: real(2), "1 1"

This attribute applies to textures of type "2d". It specifies how many times the texture image is repeated, relative to either the object size or the spatial unit, as determined by the next attribute.

texuniform: [false, true], "false"

For cube textures, this attribute controls how cube mapping is applied. The default value "false" means apply cube mapping directly, using the actual size of the object. The value "true" maps the texture to a unit object before scaling it to its actual size (geometric primitives are created by the renderer as unit objects and then scaled). In some cases this leads to more uniform texture appe ↑ Back to top general, which settings produces better results depends on the texture and the object. For 2d textures, this attribute interacts with texrepeat above. Let texrepeat be N. The default value "false" means that the 2d texture is repeated N times over the (z-facing side of the) object. The value "true" means that the 2d texture is repeated N times over one spatial unit, regardless of object size.

emission: real, "0"

Emission in OpenGL has the RGBA format, however we only provide a scalar setting. The RGB components of the OpenGL emission vector are the RGB components of the material color multiplied by the value specified here. The alpha component is 1.

specular: real, "0.5"

Specularity in OpenGL has the RGBA format, however we only provide a scalar setting. The RGB components of the OpenGL specularity vector are all equal to the value specified here. The alpha component is 1. This value should be in the range [0 1].

shininess: real, "0.5"

Shininess in OpenGL is a number between 0 and 128. The value given here is multiplied by 128 before passing it to OpenGL, so it should be in the range [0 1]. Larger values correspond to tighter specular highlight (thus reducing the overall amount of highlight but making it more salient visually). This interacts with the specularity setting; see OpenGL documentation for details.

reflectance: real, "0"

This attribute should be in the range [0 1]. If the value is greater than 0, and the material is applied to a plane or a box geom, the renderer will simulate reflectance. The larger the value, the stronger the reflectance. For boxes, only the face in the direction of the local +Z axis is reflective. Simulating reflectance properly requires ray-tracing which cannot (yet) be done in real-time. We are using the stencil buffer and suitable projections instead. Only the first reflective geom in the model is rendered as such. This adds one extra rendering pass through all geoms, in addition to the extra rendering pass added by each shadow-casting light.

rgba: real(4), "1 1 1 1"

Color and transparency of the material. All components should be in the range [0 1]. Note that textures are applied in GL_MODULATE mode, meaning that the texture color and the color specified here are multiplied component-wise. Thus the default value of "1 1 1 1" has the effect of leaving the texture unchanged. When the material is applied to a model element which defines its own local rgba attribute, the local definition has precedence. Note that this "local" definition could in fact come from a defaults class. The remaining material properties always apply.

(world)body (R)

This element is used to construct the kinematic tree via nesting. The element **worldbody** is used for the top-level body, while the element **body** is used for all other bodies. The top-level body is a restricted type of body: it cannot have child elements inertial and joint, and also cannot have any attributes. It corresponds to the origin of the world frame, within which the rest of the kinematic tree is defined. Its body name is automatically defined as "world".

name: string, optional

Name of the body.

childclass: string, optional

If this attribute is present, all descendant elements that admit a defaults class will use the class specified here, unless they specify their own class or another body with a childclass attribute is encountered along the chain of nested bodies. Recall Default settings.

mocap: [false, true], "false"

If this attribute is "true", the body is labeled as a mocap body. This is allowed only for bodies that are children of the world body and have no joints. Such bodies are fixed from the viewpoint of the dynamics, but nevertheless the forward kinematics set their position and orientation from the fields mjData.mocap_pos and mjData.mocap_quat at each time step. The size of these arrays is adjusted by the compiler so as to match the number of mocap bodies in the model. This mechanism can be used to stream motion capture data into the simulation. Mocap bodies can also be moved via mouse perturbations in the interactive visualizer, even in dynamic simulation mode. This can be useful for creating props with adjustable position and orientation. See also the mocap attribute of flag.

pos: real(3), optional

The 3D position of the body frame, in local or global coordinates as determined by the coordinate attribute of compiler. Recall the earlier discussion of local and global coordinates in Coordinate frames. In local coordinates, if the body position is left undefined it defaults to (0,0,0). In global coordinates, an undefined body position is inferred by the compiler through the following steps:

1. If the inertial frame is not defined via the inertial element, it is inferred from the geoms attached to the body. If there are no geoms, the inertial frame remains undefined. This step is applied in both local and global coordinates.
2. If both the body frame and the inertial frame are undefined, a compile error is generated.
3. If one of these two frames is defined and the other is not, the defined one is copied into the undefined one. At this point both frames are defined, in global coordinates.
4. The inertial frame as well as all elements defined in the body are converted to local coordinates, relative to the body frame.

Note that whether a frame is defined or not depends on its pos attribute, which is in the special undefined state by default. Orientation cannot be used to make this determination because it has an internal default (the unit quaternion).

quat, **axisangle**, **xyaxes**, **zaxis**, **euler**

See Frame orientations. Similar to position, the orientation specified here is interpreted in either local or global coordinates as determined by the coordinate attribute of compiler. Unlike position which is required in local coordinates, the orientation defaults to the unit quaternion, thus specifying it is optional even in local coordinates. If the body frame was copied from the body inertial frame per the above rules, the copy operation applies to both position and orientat ↑ Back to top tting of the orientation-related attributes is ignored.

gravcomp: real, "0"

Gravity compensation force, specified as fraction of body weight. This attribute creates an upwards force applied to the body's center of mass, countering the force of gravity. As an example, a value of `1` creates an upward force equal to the body's weight and compensates for gravity exactly. Values greater than `1` will create a net upwards force or buoyancy effect.

user: real(nbody_user), "0 0 ..."

See User parameters.

body/ inertial (?)

This element specifies the mass and inertial properties of the body. If this element is not included in a given body, the inertial properties are inferred from the geoms attached to the body. When a compiled MJCF model is saved, the XML writer saves the inertial properties explicitly using this element, even if they were inferred from geoms. The inertial frame is such that its center coincides with the center of mass of the body, and its axes coincide with the principal axes of inertia of the body. Thus the inertia matrix is diagonal in this frame.

pos: real(3), required

Position of the inertial frame. This attribute is required even when the inertial properties can be inferred from geoms. This is because the presence of the **inertial** element itself disables the automatic inference mechanism.

quat, **axisangle**, **xyaxes**, **zaxis**, **euler**

Orientation of the inertial frame. See Frame orientations.

mass: real, required

Mass of the body. Negative values are not allowed. MuJoCo requires the inertia matrix in generalized coordinates to be positive-definite, which can sometimes be achieved even if some bodies have zero mass. In general however there is no reason to use massless bodies. Such bodies are often used in other engines to bypass the limitation that joints cannot be combined, or to attach sensors and cameras. In MuJoCo primitive joint types can be combined, and we have sites which are a more efficient attachment mechanism.

diaginertia: real(3), optional

Diagonal inertia matrix, expressing the body inertia relative to the inertial frame. If this attribute is omitted, the next attribute becomes required.

fullinertia: real(6), optional

Full inertia matrix M. Since M is 3-by-3 and symmetric, it is specified using only 6 numbers in the following order: M(1,1), M(2,2), M(3,3), M(1,2), M(1,3), M(2,3). The compiler computes the eigenvalue decomposition of M and sets the frame orientation and diagonal inertia accordingly. If non-positive eigenvalues are encountered (i.e., if M is not positive definite) a compile error is generated.

body/ joint (*)

This element creates a joint. As explained in Kinematic tree, a joint creates motion degrees of freedom between the body where it is defined and the body's parent. If multiple joints are defined in the same body, the corresponding spatial transformations (of the body frame relative to the parent frame) are applied in order. If no joints are defined, the body is welded to its parent. Joints cannot be defined in the world body. At runtime the positions and orientations of all joints defined in the model are stored in the vector mjData.qpos, in the order in which the appear in the kinematic tree. The linear and angular velocities are stored in the vector mjData.qvel. These two vectors have different dimensionality when free or ball joints are used, because such joints represent rotations as unit quaternions.

name: string, optional

Name of the joint.

class: string, optional

Defaults class for setting unspecified attributes.

type: [free, ball, slide, hinge], "hinge"

Type of the joint. The keywords have the following meaning: The **free** type creates a free "joint" with three translational degrees of freedom followed by three rotational degrees of freedom. In other words it makes the body floating. The rotation is represented as a unit quaternion. This joint type is only allowed in bodies that are children of the world body. No other joints can be defined in the body if a free joint is defined. Unlike the remaining joint types, free joints do not have a position within the body frame. Instead the joint position is assumed to coincide with the center of the body frame. Thus at runtime the position and orientation data of the free joint correspond to the global position and orientation of the body frame. Free joints cannot have limits.

The **ball** type creates a ball joint with three rotational degrees of freedom. The rotation is represented as a unit quaternion. The quaternion (1,0,0,0) corresponds to the initial configuration in which the model is defined. Any other quaternion is interpreted as a 3D rotation relative to this initial configuration. The rotation is around the point defined by the pos attribute below. If a body has a ball joint, it cannot have other rotational joints (ball or hinge). Combining ball joints with slide joints in the same body is allowed.

The **slide** type creates a sliding or prismatic joint with one translational degree of freedom. Such joints are defined by a position and a sliding direction. For simulation purposes only the direction is needed; the joint position is used for rendering purposes.

The **hinge** type creates a hinge joint with one rotational degree of freedom. The rotation takes place around a specified axis through a specified position. This is the most common type of joint and is therefore the default. Most models contain only hinge and free joints.

group: int, "0"

Integer group to which the joint belongs. This attribute can be used for custom tags. It is also used by the visualizer to enable and disable the rendering of entire groups of joints.

pos: real(3), "0 0 0"

Position of the joint, specified in local or global coordinates as determined by the coordinate attribute of compiler. this attribute is ignored.

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axis: real(3), "0 0 1"

This attribute specifies the axis of rotation for hinge joints and the direction of translation for slide joints. It is ignored for free and ball joints. The vector specified here is automatically normalized to unit length as long as its length is greater than 10E-14; otherwise a compile error is generated.

springdamper: real(2), "0 0"

When both numbers are positive, the compiler will override any stiffness and damping values specified with the attributes below, and will instead set them automatically so that the resulting mass-spring-damper for this joint has the desired time constant (first value) and damping ratio (second value). This is done by taking into account the joint inertia in the model reference configuration. Note that the format is the same as the solref parameter of the constraint solver.

limited: [false, true, auto], "auto"

This attribute specifies if the joint has limits. It interacts with the range attribute below. If this attribute is "false", joint limits are disabled. If this attribute is "true", joint limits are enabled. If this attribute is "auto", and autolimits is set in compiler, joint limits will be enabled if range is defined.

solreflimit, **solimplimit**

Constraint solver parameters for simulating joint limits. See Solver parameters.

solreffriction, **solimpfriction**

Constraint solver parameters for simulating dry friction. See Solver parameters.

stiffness: real, "0"

Joint stiffness. If this value is positive, a spring will be created with equilibrium position given by springref below. The spring force is computed along with the other passive forces.

range: real(2), "0 0"

The joint limits. Limits can be imposed on all joint types except for free joints. For hinge and ball joints, the range is specified in degrees or radians depending on the angle attribute of compiler. For ball joints, the limit is imposed on the angle of rotation (relative to the reference configuration) regardless of the axis of rotation. Only the second range parameter is used for ball joints; the first range parameter should be set to 0. See the Limit section in the Computation chapter for more information.
Setting this attribute without specifying limited is an error, unless autolimits is set in compiler.

margin: real, "0"

The distance threshold below which limits become active. Recall that the Constraint solver normally generates forces as soon as a constraint becomes active, even if the margin parameter makes that happen at a distance. This attribute together with solreflimit and solimplimit can be used to model a soft joint limit.

ref: real, "0"

The reference position or angle of the joint. This attribute is only used for slide and hinge joints. It defines the joint value corresponding to the initial model configuration. The amount of spatial transformation that the joint applies at runtime equals the current joint value stored in mjData.qpos minus this reference value stored in mjModel.qpos0. The meaning of these vectors was discussed in the Stand-alone section in the Overview chapter.

springref: real, "0"

The joint position or angle in which the joint spring (if any) achieves equilibrium. Similar to the vector mjModel.qpos0 which stores all joint reference values specified with the ref attribute above, all spring reference values specified with this attribute are stored in the vector mjModel.qpos_spring. The model configuration corresponding to mjModel.qpos_spring is also used to compute the spring reference lengths of all tendons, stored in mjModel.tendon_lengthspring. This is because tendons can also have springs.

armature: real, "0"

Armature inertia (or rotor inertia, or reflected inertia) of all degrees of freedom created by this joint. These are constants added to the diagonal of the inertia matrix in generalized coordinates. They make the simulation more stable, and often increase physical realism. This is because when a motor is attached to the system with a transmission that amplifies the motor force by c, the inertia of the rotor (i.e., the moving part of the motor) is amplified by c*c. The same holds for gears in the early stages of planetary gear boxes. These extra inertias often dominate the inertias of the robot parts that are represented explicitly in the model, and the armature attribute is the way to model them.

damping: real, "0"

Damping applied to all degrees of freedom created by this joint. Unlike friction loss which is computed by the constraint solver, damping is simply a force linear in velocity. It is included in the passive forces. Despite this simplicity, larger damping values can make numerical integrators unstable, which is why our Euler integrator handles damping implicitly. See Integration in the Computation chapter.

frictionloss: real, "0"

Friction loss due to dry friction. This value is the same for all degrees of freedom created by this joint. Semantically friction loss does not make sense for free joints, but the compiler allows it. To enable friction loss, set this attribute to a positive value.

user: real(njnt_user), "0 0 ..."

See User parameters.

body/ freejoint (*)

This element creates a free joint whose only attributes are name and group. The **freejoint** element is an XML shortcut for

```
<joint type="free" stiffness="0" damping="0" frictionloss="0" armature="0"/>
```

While this joint can evidently be created with the joint element, default joint settings could affect it. This is usually undesirable as physical free bodies do not have nonzero stiffness, damping, friction or armature. To avoid this complication, the **freejoint** element was introduced, ensuring joint defaults are *not inherited*. lel is saved, it will appear as a regular joint of type free.

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name: string, optional

Name of the joint.

group: int, "0"

Integer group to which the joint belongs. This attribute can be used for custom tags. It is also used by the visualizer to enable and disable the rendering of entire groups of joints.

body/ geom (*)

This element creates a geom, and attaches it rigidly to the body within which the geom is defined. Multiple geoms can be attached to the same body. At runtime they determine the appearance and collision properties of the body. At compile time they can also determine the inertial properties of the body, depending on the presence of the inertial element and the setting of the inertiafromgeom attribute of compiler. This is done by summing the masses and inertias of all geoms attached to the body with geom group in the range specified by the inertiagrouprange attribute of compiler. The geom masses and inertias are computed using the geom shape, a specified density or a geom mass which implies a density, and the assumption of uniform density.

Geoms are not strictly required for physics simulation. One can create and simulate a model that only has bodies and joints. Such a model can even be visualized, using equivalent inertia boxes to represent bodies. Only contact forces would be missing from such a simulation. We do not recommend using such models, but knowing that this is possible helps clarify the role of bodies and geoms in MuJoCo.

name: string, optional

Name of the geom.

class: string, optional

Defaults class for setting unspecified attributes.

type: [plane, hfield, sphere, capsule, ellipsoid, cylinder, box, mesh], "sphere"

Type of geometric shape. The keywords have the following meaning: The **plane** type defines a plane which is infinite for collision detection purposes. It can only be attached to the world body or static children of the world. The plane passes through a point specified via the pos attribute. It is normal to the Z axis of the geom's local frame. The +Z direction corresponds to empty space. Thus the position and orientation defaults of (0,0,0) and (1,0,0,0) would create a ground plane at Z=0 elevation, with +Z being the vertical direction in the world (which is MuJoCo's convention). Since the plane is infinite, it could have been defined using any other point in the plane. The specified position however has additional meaning with regard to rendering. If either of the first two size parameters are positive, the plane is rendered as a rectangle of finite size (in the positive dimensions). This rectangle is centered at the specified position. Three size parameters are required. The first two specify the half- size of the rectangle along the X and Y axes. The third size parameter is unusual: it specifies the spacing between the grid subdivisions of the plane for rendering purposes. The subdivisions are revealed in wireframe rendering mode, but in general they should not be used to paint a grid over the ground plane (textures should be used for that purpose). Instead their role is to improve lighting and shadows, similar to the subdivisions used to render boxes. When planes are viewed from the back, the are automatically made semi-transparent. Planes and the +Z faces of boxes are the only surfaces that can show reflections, if the material applied to the geom has positive reflection. To render an infinite plane, set the first two size parameters to zero.

The **hfield** type defines a height field geom. The geom must reference the desired height field asset with the hfield attribute below. The position and orientation of the geom set the position and orientation of the height field. The size of the geom is ignored, and the size parameters of the height field asset are used instead. See the description of the hfield element. Similar to planes, height field geoms can only be attached to the world body or to static children of the world.

The **sphere** type defines a sphere. This and the next four types correspond to built-in geometric primitives. These primitives are treated as analytic surfaces for collision detection purposes, in many cases relying on custom pair- wise collision routines. Models including only planes, spheres, capsules and boxes are the most efficient in terms of collision detection. Other geom types invoke the general-purpose convex collider. The sphere is centered at the geom's position. Only one size parameter is used, specifying the radius of the sphere. Rendering of geometric primitives is done with automatically generated meshes whose density can be adjusted via quality. The sphere mesh is triangulated along the lines of latitude and longitude, with the Z axis passing through the north and south pole. This can be useful in wireframe mode for visualizing frame orientation.

The **capsule** type defines a capsule, which is a cylinder capped with two half-spheres. It is oriented along the Z axis of the geom's frame. When the geom frame is specified in the usual way, two size parameters are required: the radius of the capsule followed by the half-height of the cylinder part. However capsules as well as cylinders can also be thought of as connectors, allowing an alternative specification with the fromto attribute below. In that case only one size parameter is required, namely the radius of the capsule.

The **ellipsoid** type defines a ellipsoid. This is a sphere scaled separately along the X, Y and Z axes of the local frame. It requires three size parameters, corresponding to the three radii. Note that even though ellipsoids are smooth, their collisions are handled via the general-purpose convex collider. The only exception are plane-ellipsoid collisions which are computed analytically.

The **cylinder** type defines a cylinder. It requires two size parameters: the radius and half-height of the cylinder. The cylinder is oriented along the Z axis of the geom's frame. It can alternatively be specified with the fromto attribute below.

The **box** type defines a box. Three size parameters are required, corresponding to the half-sizes of the box along the X, Y and Z axes of the geom's frame. Note that box-box collisions are the only pair-wise collision type that can generate a large number of contact points, up to 8 depending on the configuration. The contact generation itself is fast but this can slow down the constraint solver. As an alternative, we provide the boxconvex attribute in flag which causes the general-purpose convex collider to be used instead, yielding at most one contact point per geom pair.

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The **mesh** type defines a mesh. The geom must reference the desired mesh asset with the mesh attribute. Note that mesh assets can also be referenced from other geom types, causing primitive shapes to be fitted; see below. The size is determined by the mesh asset and the geom size parameters are ignored. Unlike all other geoms, the position and orientation of mesh geoms after compilation do not equal the settings of the corresponding attributes here. Instead they are offset by the translation and rotation that were needed to center and align the mesh asset in its own coordinate frame. Recall the discussion of centering and alignment in the mesh element.

contype: int, "1"

This attribute and the next specify 32-bit integer bitmasks used for contact filtering of dynamically generated contact pairs. See Collision detection in the Computation chapter. Two geoms can collide if the contype of one geom is compatible with the conaffinity of the other geom or vice versa. Compatible means that the two bitmasks have a common bit set to 1.

conaffinity: int, "1"

Bitmask for contact filtering; see contype above.

condim: int, "3"

The dimensionality of the contact space for a dynamically generated contact pair is set to the maximum of the condim values of the two participating geoms. See Contact in the Computation chapter. The allowed values and their meaning are:

condim	Description
1	Frictionless contact.
3	Regular frictional contact, opposing slip in the tangent plane.
4	Frictional contact, opposing slip in the tangent plane and rotation around the contact normal. This is useful for modeling soft contacts (independent of contact penetration).
6	Frictional contact, opposing slip in the tangent plane, rotation around the contact normal and rotation around the two axes of the tangent plane. The latter frictional effects are useful for preventing objects from indefinite rolling.

group: int, "0"

This attribute specifies an integer group to which the geom belongs. The only effect on the physics is at compile time, when body masses and inertias are inferred from geoms selected based on their group; see inertiagrouprange attribute of compiler. At runtime this attribute is used by the visualizer to enable and disable the rendering of entire geom groups. It can also be used as a tag for custom computations.

priority: int, "0"

The geom priority determines how the properties of two colliding geoms are combined to form the properties of the contact. This interacts with the solmix attribute. See Contact parameters.

size: real(3), "0 0 0"

Geom size parameters. The number of required parameters and their meaning depends on the geom type as documented under the type attribute. Here we only provide a summary. All required size parameters must be positive; the internal defaults correspond to invalid settings. Note that when a non-mesh geom type references a mesh, a geometric primitive of that type is fitted to the mesh. In that case the sizes are obtained from the mesh, and the geom size parameters are ignored. Thus the number and description of required size parameters in the table below only apply to geoms that do not reference meshes.

Type	Number	Description
plane	3	X half-size; Y half-size; spacing between square grid lines for rendering. If either the X or Y half-size is 0, the plane is rendered as infinite in the dimension(s) with 0 size.
hfield	0	The geom sizes are ignored and the height field sizes are used instead.
sphere	1	Radius of the sphere.
capsule	1 or 2	Radius of the capsule; half-length of the cylinder part when not using the fromto specification.
ellipsoid	1	X radius; Y radius; Z radius.
cylinder	1 or 2	Radius of the cylinder; half-length of the cylinder when not using the fromto specification.
box	3	X half-size; Y half-size; Z half-size.
mesh	0	The geom sizes are ignored and the mesh sizes are used instead.

material: string, optional

If specified, this attribute applies a material to the geom. The material determines the visual properties of the geom. The only exception is color: if the rgba attribute below is different from its internal default, it takes precedence while the remaining material properties are still applied. Note that if the same material is referenced from multiple geoms (as well as sites and tendons) and the user changes some of its properties at runtime, these changes will take effect immediately for all model elements referencing the material. This is because the compiler saves the material and its properties as a separate element in mjModel, and the elements using this material only keep a reference to it.

rgba: real(4), "0.5 0.5 0.5 1"

Instead of creating material assets and referencing them, this attribute can be used to set color and transparency only. This is not as flexible as the material mechanism, but is more convenient and is often sufficient. If the value of this attribute is different from the internal default, it takes precedence over the material.

friction: real(3), "1 0.005 0.0001"

Contact friction parameters for dynamically generated contact pairs. The first number is the sliding friction, acting ↑ Back to top es of the tangent plane. The second number is the torsional friction, acting around the contact normal. The third number is the rolling friction, acting around both axes of the tangent plane. The friction parameters for the contact pair are combined depending on the solmix and priority attributes, as explained in Contact parameters.

mass: real, optional

If this attribute is specified, the density attribute below is ignored and the geom density is computed from the given mass, using the geom shape and the assumption of uniform density. The computed density is then used to obtain the geom inertia. Recall that the geom mass and inertia are only used during compilation, to infer the body mass and inertia if necessary. At runtime only the body inertial properties affect the simulation; the geom mass and inertia are not even saved in mjModel.

density: real, "1000"

Material density used to compute the geom mass and inertia. The computation is based on the geom shape and the assumption of uniform density. The internal default of 1000 is the density of water in SI units. This attribute is used only when the mass attribute above is unspecified.

shellinertia [false, true], "false"

If true, the geom's inertia is computed assuming that all the mass is concentrated on the boundary. In this case density is interpreted as surface density rather than volumetric density.

solmix: real, "1"

This attribute specifies the weight used for averaging of contact parameters, and interacts with the priority attribute. See Contact parameters.

solref, **solimp**

Constraint solver parameters for contact simulation. See Solver parameters.

margin: real, "0"

Distance threshold below which contacts are detected and included in the global array mjData.contact. This however does not mean that contact force will be generated. A contact is considered active only if the distance between the two geom surfaces is below margin-gap. Recall that constraint impedance can be a function of distance, as explained in Solver parameters. The quantity this function is applied to is the distance between the two geoms minus the margin plus the gap.

gap: real, "0"

This attribute is used to enable the generation of inactive contacts, i.e., contacts that are ignored by the constraint solver but are included in mjData.contact for the purpose of custom computations. When this value is positive, geom distances between margin and margin-gap correspond to such inactive contacts.

fromto: real(6), optional

This attribute can only be used with capsule, cylinder, ellipsoid and box geoms. It provides an alternative specification of the geom length as well as the frame position and orientation. The six numbers are the 3D coordinates of one point followed by the 3D coordinates of another point. The elongated part of the geom connects these two points, with the +Z axis of the geom's frame oriented from the first towards the second point. The frame orientation is obtained with the same procedure as the zaxis attribute described in Frame orientations. The frame position is in the middle between the two points. If this attribute is specified, the remaining position and orientation-related attributes are ignored.

pos: real(3), "0 0 0"

Position of the geom frame, in local or global coordinates as determined by the coordinate attribute of compiler.

quat, **axisangle**, **xyaxes**, **zaxis**, **euler**

Orientation of the geom frame. See Frame orientations.

hfield: string, optional

This attribute must be specified if and only if the geom type is "hfield". It references the height field asset to be instantiated at the position and orientation of the geom frame.

mesh: string, optional

If the geom type is "mesh", this attribute is required. It references the mesh asset to be instantiated. This attribute can also be specified if the geom type corresponds to a geometric primitive, namely one of "sphere", "capsule", "cylinder", "ellipsoid", "box". In that case the primitive is automatically fitted to the mesh asset referenced here. The fitting procedure uses either the equivalent inertia box or the axis-aligned bounding box of the mesh, as determined by the attribute fitaabb of compiler. The resulting size of the fitted geom is usually what one would expect, but if not, it can be further adjusted with the fitscale attribute below. In the compiled mjModel the geom is represented as a regular geom of the specified primitive type, and there is no reference to the mesh used for fitting.

fitscale: real, "1"

This attribute is used only when a primitive geometric type is being fitted to a mesh asset. The scale specified here is relative to the output of the automated fitting procedure. The default value of 1 leaves the result unchanged, a value of 2 makes all sizes of the fitted geom two times larger.

fluidshape: [none, ellipsoid], "none"

"ellipsoid" Activates geom-level stateless fluid interaction model based on an ellipsoidal approximation of the geom shape. When active, the model based on body inertia sizes is disabled for the parent body.

fluidcoef: real(5), "0.5 0.25 1.5 1.0 1.0"

Dimensionless coefficients of fluid interaction model, as follows.

Index	Description	Default
0	Blunt drag coefficient.	0.5
1	Slender drag coeficient.	0.25

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Index	Description	Default
2	Angular drag coefficient.	1.5
3	Kutta lift coeficient.	1.0
4	Magnus lift coeficient.	1.0

user: real(nuser_geom), "0 0 ..."

See User parameters.

body/ site (*)

This element creates a site, which is a simplified and restricted kind of geom. A small subset of the geom attributes are available here; see the geom element for their detailed documentation. Semantically sites represent locations of interest relative to the body frames. Sites do not participate in collisions and computation of body masses and inertias. The geometric shapes that can be used to render sites are limited to a subset of the available geom types. However sites can be used in some places where geoms are not allowed: mounting sensors, specifying via-points of spatial tendons, constructing slider-crank transmissions for actuators.

name: string, optional

Name of the site.

class: string, optional

Defaults class for setting unspecified attributes.

type: [sphere, capsule, ellipsoid, cylinder, box], "sphere"

Type of geometric shape. This is used for rendering, and also determines the active sensor zone for touch sensors.

group: int, "0"

Integer group to which the site belongs. This attribute can be used for custom tags. It is also used by the visualizer to enable and disable the rendering of entire groups of sites.

material: string, optional

Material used to specify the visual properties of the site.

rgba: real(4), "0.5 0.5 0.5 1"

Color and transparency. If this value is different from the internal default, it overrides the corresponding material properties.

size: real(3), "0.005 0.005 0.005"

Sizes of the geometric shape representing the site.

fromto: real(6), optional

This attribute can only be used with capsule, cylinder, ellipsoid and box sites. It provides an alternative specification of the site length as well as the frame position and orientation. The six numbers are the 3D coordinates of one point followed by the 3D coordinates of another point. The elongated part of the site connects these two points, with the +Z axis of the site's frame oriented from the first towards the second point. The frame orientation is obtained with the same procedure as the zaxis attribute described in Frame orientations. The frame position is in the middle between the two points. If this attribute is specified, the remaining position and orientation-related attributes are ignored.

pos: real(3), "0 0 0"

Position of the site frame.

quat, **axisangle**, **xyaxes**, **zaxis**, **euler**

Orientation of the site frame. See Frame orientations.

user: real(nuser_site), "0 0 ..."

See User parameters.

body/ camera (*)

This element creates a camera, which moves with the body where it is defined. To create a fixed camera, define it in the world body. The cameras created here are in addition to the default free camera which is always defined and is adjusted via the visual element. Internally MuJoCo uses a flexible camera model, where the viewpoint and projection surface are adjusted independently so as to obtain oblique projections needed for virtual environments. This functionality however is not accessible through MJCF. Instead, the cameras created with this element (as well as the free camera) have a viewpoint that is always centered in front of the projection surface. The viewpoint coincides with the center of the camera frame. The camera is looking along the -Z axis of its frame. The +X axis points to the right, and the +Y axis points up. Thus the frame position and orientation are the key adjustments that need to be made here.

name: string, optional

Name of the camera.

class: string, optional

Defaults class for setting unspecified attributes.

mode: [fixed, track, trackcom, targetbody, targetbodycom], "fixed"

This attribute specifies how the camera position and orientation in world coordinates are computed in forward kinematics (which in turn determine what the camera sees). "fixed" means that the position and orientation specified below are fixed relative to the parent (i.e., the body where the camera is defined). "track" means that the camera position is at a constant offset from the parent in world coordinates, while the camera orientation is constant in world coordinates. These constants are determined by applying forward kinematics in qpos0 and treating the camera as fixed. Tracking can be used for example to position a camera above a body, point it down so it sees the body, and have it always remain above the body no matter how the body translates and rotates. "trackcom" is similar to "track" but the constant spatial offset is defined relative to the center of mass of the kinematic subtree starting at the parent body. This can be used to keep an entire mechanism in view. Note that the subtree center of mass for the world body is the center of mass of the entire model. So if a camera is defined in the world body in mode "trackcom", it will track the entire model. "targetbody" means that the camera position is fixed in the parent body, while the camera orientation is adjusted so that it always points towards the targeted body (which is specified with the target attrib s can be used for example to model an eye that fixates a moving object; the object will be the target, and the camera/eye will be defined in the body corresponding to the head. "targetbodycom" is the same as "targetbody" but the camera is oriented towards the center of mass of the subtree starting at the target body.

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target: string, optional

When the camera mode is "targetbody" or "targetbodycom", this attribute becomes required. It specifies which body should be targeted by the camera. In all other modes this attribute is ignored.

fovy: real, "45"

Vertical field of view of the camera, expressed in degrees regardless of the global angle setting. The horizontal field of view is computed automatically given the window size and the vertical field of view.

ipd: real, "0.068"

Inter-pupilary distance. This attribute only has an effect during stereoscopic rendering. It specifies the distance between the left and right viewpoints. Each viewpoint is shifted by +/- half of the distance specified here, along the X axis of the camera frame.

pos: real(3), "0 0 0"

Position of the camera frame.

quat, **axisangle**, **xyaxes**, **zaxis**, **euler**

Orientation of the camera frame. See Frame orientations.

user: real(nuser_cam), "0 0 …"

See User parameters.

body/ light (*)

This element creates a light, which moves with the body where it is defined. To create a fixed light, define it in the world body. The lights created here are in addition to the default headlight which is always defined and is adjusted via the visual element. MuJoCo relies on the standard lighting model in OpenGL (fixed functionality) augmented with shadow mapping. The effects of lights are additive, thus adding a light always makes the scene brighter. The maximum number of lights that can be active simultaneously is 8, counting the headlight. The light is shining along the direction specified by the dir attribute. It does not have a full spatial frame with three orthogonal axes.

name: string, optional

Name of the light.

class: string, optional

Defaults class for setting unspecified attributes.

mode: [fixed, track, trackcom, targetbody, targetbodycom], "fixed"

This is identical to the mode attribute of camera above. It specifies the how the light position and orientation in world coordinates are computed in forward kinematics (which in turn determine what the light illuminates).

target: string, optional

This is identical to the target attribute of camera above. It specifies which body should be targeted in "targetbody" and "targetbodycom" modes.

directional: [false, true], "false"

The light is directional if this attribute is "true", otherwise it is a spotlight.

castshadow: [false, true], "true"

If this attribute is "true" the light will cast shadows. More precisely, the geoms illuminated by the light will cast shadows, however this is a property of lights rather than geoms. Since each shadow-casting light causes one extra rendering pass through all geoms, this attribute should be used with caution. Higher quality of the shadows is achieved by increasing the value of the shadowsize attribute of quality, as well as positioning spotlights closer to the surface on which shadows appear, and limiting the volume in which shadows are cast. For spotlights this volume is a cone, whose angle is the cutoff attribute below multiplied by the shadowscale attribute of map. For directional lights this volume is a box, whose half-sizes in the directions orthogonal to the light are the model extent multiplied by the shadowclip attribute of map. The model extent is computed by the compiler but can also be overridden by specifying the extent attribute of statistic. Internally the shadow-mapping mechanism renders the scene from the light viewpoint (as if it were a camera) into a depth texture, and then renders again from the camera viewpoint, using the depth texture to create shadows. The internal rendering pass uses the same near and far clipping planes as regular rendering, i.e., these clipping planes bound the cone or box shadow volume in the light direction. As a result, some shadows (especially those very close to the light) may be clipped.

active: [false, true], "true"

The light is active if this attribute is "true". This can be used at runtime to turn lights on and off.

pos: real(3), "0 0 0"

Position of the light. This attribute only affects the rendering for spotlights, but it should also be defined for directional lights because we render the cameras as decorative elements.

dir: real(3), "0 0 -1"

Direction of the light.

attenuation: real(3), "1 0 0"

These are the constant, linear and quadratic attenuation coefficients in OpenGL. The default corresponds to no attenuation. See the OpenGL documentation for more information on this and all other OpenGL-related properties.

cutoff: real, "45"

Cutoff angle for spotlights, always in degrees regardless of the global angle setting.

exponent: real, "10"

Exponent for spotlights. This setting controls the softness of the spotlight cutoff.

ambient: real(3), "0 0 0"

The ambient color of the light.

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diffuse: real(3), “0.7 0.7 0.7”

The diffuse color of the light.

specular: real(3), “0.3 0.3 0.3”

The specular color of the light.

body/ composite (*)

This is not a model element, but rather a macro which expands into multiple model elements representing a composite object. These elements are bodies (with their own joints, geoms and sites) that become children of the parent body containing the macro, as well as tendons and equality constraints added to the corresponding model sections. The automatically-generated bodies are laid out in a regular grid in 1D, 2D or 3D depending on the object type and count attributes. The macro expansion is done by the model compiler. If the resulting model is then saved, the macro will be replaced with the actual model elements. The defaults mechanism used in the rest of MJCF does not apply here, even if the parent body has a childclass attribute defined. Instead there are internal defaults adjusted automatically for each composite object type. Composite objects can only be defined if the model is in local coordinates. Using them in global coordinates results in compiler error. See Composite objects in the modeling guide for more detailed explanation.

prefix: string, optional

All automatically generated model elements have names indicating the element type and index. For example, the body at coordinates (2, 0) in a 2D grid is named “B2_0” by default. If prefix=“C” is specified, the same body is named “CB2_0”. The prefix is needed when multiple composite objects are used in the same model, to avoid name conflicts.

type: [particle, grid, cable, rope, loop, cloth, box, cylinder, ellipsoid], required

This attribute determines the type of composite object. The remaining attributes and sub-elements are then interpreted according to the type. Default settings are also adjusted depending on the type.

The **particle** type creates a 1D, 2D or 3D grid of equally-spaced bodies. By default, each body has a single sphere geom and 3 orthogonal sliding joints, allowing translation but not rotation. The geom condim and priority attributes are set to 1 by default. This makes the spheres have frictionless contacts with all other geoms (unless the priority of some frictional geom is higher). The user can replace the default sliders with multiple joints of kind=”particle” and replace the default sphere with a custom geom.

The **grid** type creates a 1D or 2D grid of bodies, each having a sphere geom, a sphere site, and 3 orthogonal sliding joints by default. The **pin** sub-element can be used to specify that some bodies should not have joints, and instead should be pinned to the parent body. Unlike the particle type, here each two neighboring bodies are connected with a spatial tendon whose length is equality-constrained to its initial value (the sites are needed to define the tendons). The “main” tendons are parallel to the axes of the grid. In addition one can create diagonal “shear” tendons, using the **tendon** sub-element. This type is suitable for simulating strings as well as cloth.

The **rope** type creates a 1D grid of bodies, each having a geom with user-defined type (sphere, capsule or ellipsoid) and 2 hinge joints with axes orthogonal to the grid, creating a universal joint with the previous body. This corresponds to a kinematic chain which can bend but cannot stretch or twist. In addition, one can specify stretch and twist joints (slide and hinge respectively) with the **joint** sub-element. When specified, these extra joints are equality-constrained, but the constraint is soft by default so that some stretch and twist are possible. The rope can extend in one or both directions from the parent body. To specify the origin of the rope, the parent body *must* be named so that it fits the automatic naming convention. For example, to make the parent be the first body in the chain, and assuming we have prefix=”C”, the parent body should be named “CB0”. When the parent is not at the end, the rope consists of two kinematic chains starting at the parent and extending in opposite directions.

The **loop** type is the same as the rope type except the elements are arranged in a circle, and the first and last elements are equality-constrained to remain connected (using the “connect” constraint type). The softness of this equality constraint is adjusted with the attributes solrefsmooth and solimpsmooth.

The **cable** type creates a 1D chain of bodies connected with ball joints, each having a geom with user-defined type (cylinder, capsule or box). The geometry can either be defined with an array of 3D vertex coordinates vertex or with prescribed functions with the option curve. Currently, only linear and trigonometric functions are supported. For example, an helix can be obtained with curve=”cos(s) sin(s) s”. The size is set with the option size, resulting in $f(s) = \{\text{size}[1] \cdot \cos(2\pi \cdot \text{size}[2]),\ \text{size}[1] \cdot \sin(2\pi \cdot \text{size}[2]),\ \text{size}[0] \cdot s\}$.

The **cloth** type is a different way to model cloth, beyond type=”grid”. Here the elements are connected with universal joints and form a kinematic spanning tree. The root of the tree is the parent body, and its coordinates in the grid are inferred from its name - similar to rope but here the naming format is “CB2_0”. Neighboring bodies that are not connected with joints are then connected with equality-constrained spatial tendons. The resulting cloth is non-homogeneous, because the kinematic constraints cannot be violated while the tendon equality constraints are soft. One can make it more homogeneous by adding stretch and twist joints (similar to rope) and adjusting the strength of their equality constraints. Shear tendons can also be added. In addition to the different physics, cloth can do things that a 2D grid cannot do. This is because the elements of cloth have both position and orientation, while the elements of grid can only translate. The geoms used in cloth can be ellipsoids and capsules in addition to spheres. When elongated geoms are used, they are rotated and interleaved in a pattern that fills the holes, preventing objects from penetrating the cloth. Furthermore the inertia of the cloth elements can be modified with the flatinertia attribute, and can then be used with lift and drag forces to simulate ripple effects.

The **box** type creates a 3D arrangement of bodies forming the outer shell of a (soft) box. The parent body is at the center of the box. Each element body has a geom (sphere, ellipsoid or capsule) and a single sliding joint pointing away from the center of the box. The sliding joints are equality-constrained to their initial value. Furthermore, to achieve smooth deformations of the sides of the box, each joint is equality-constrained to remain equal to its neighbor joints.

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To preserve the volume of the soft box approximately, a fixed tendon is used to constrain the sum of all joints to re. When the user specifies elongated geoms (capsules or ellipsoids) their long axis is aligned with the sliding joint axis. This makes the shell thicker for collision detection purposes, preventing objects from penetrating the box. It is important to disable contacts between the elements of the box. This is done by setting the default geom contype to 0. The user can change it of course, but if the geoms comprising the soft box are allowed to contact each other the model will not work as intended.

The **cylinder** and **ellipsoid** types are the same as box, except the elements are projected on the surface of an ellipsoid or a cylinder respectively. Thus the composite soft body shape is different, while everything else is the same as in the box type.

count: int(3), required

The element count in each dimension of the grid. This can have 1, 2 or 3 numbers, specifying the element count along the X, Y and Z axis of the parent body frame within. Any missing numbers default to 1. If any of these numbers is 1, all subsequent numbers must also be 1, so that the leading dimensions of the grid are used. This means for example that a 1D grid will always extend along the X axis. To achieve a different orientation, rotate the frame of the parent body. Note that some types imply a grid of certain dimensionality, so the requirements for this attribute depend on the specified type.

spacing: real, required

The spacing between the centers of the grid elements. This spacing is the same in all dimensions. It should normally be set to a value larger than the geom size, otherwise there will be a lot of contacts in the reference model configuration (which is allowed but rarely desirable).

offset: real(3), "0 0 0"

This attribute affects particle and grid types, and is ignored for all other types. It specifies a 3D offset from the center of the parent body to the center of the grid of elements. The offset is expressed in the local coordinate frame of the parent body.

flatinertia: real, "0"

This attribute affects the cloth type and is ignored for all other types. The default value 0 disables this mechanism. When the value is positive, it specifies the ratio of the small-to-large axes of the modified diagonal inertia. The idea is to set it to a small value, say 0.01, in which case the inertias of the body elements will corresponds to flat boxes aligned with the cloth (which can then be used for lift forces). This will not change the geom shapes, but instead will set the body inertias directly and disable the automatic computation of inertia from geom shape for the composite body only.

solrefsmooth, **solimpsmooth**

These are the solref and solimp attributes of the loop-closure equality constraint for loop types, and the smoothness-preserving equality constraint for box, cylinder and ellipsoid types. For all other types they have no effect. They obey the same rules as all other solref and solimp attributes in MJCF, except their defaults here are adjusted depending on the composite type. See Solver parameters.

vertex: real(3*nvert), optional

Vertex 3D positions in global coordinates (cable only).

initial: [free, ball, none], "0"

Behavior of the first point (cable only). Free: free joint. Ball: ball joint. None: no dof.

curve: string(3), optional

Functions specifying the vertex positions (cable only). Available functions are *s*, *cos(s)*, and *sin(s)*, where *s* is the arc length parameter.

size: int(3), optional

Scaling of the curve functions (cable only). *size[0]* is the scaling of *s*, *size[1]* is the radius of *cos(s)* and *sin(s)*, and *size[2]* is the speed of the argument (i.e. *cos(2*pi*size[2]*s)*).

body/composite/ joint (*)

Depending on the composite type, some joints are created automatically (e.g. the universal joints in rope) while other joints are optional (e.g. the stretch and twist joints in rope). This sub-element is used to specify which optional joints should be created, as well as to adjust the attributes of both automatic and optional joints.

kind: [main, twist, stretch, particle], required

The joint kind here is orthogonal to the joint type in the rest of MJCF. The joint kind refers to the function of the joint within the mechanism comprising the composite body, while the joint type (hinge or slide) is implied by the joint kind and composite body type.

The **main** kind corresponds to the main joints forming each composite type. These joints are automatically included in the model even if the joint sub-element is missing. The main joints are 3D sliders for particle and grid; 1D sliders for box, cylinder and rope; universal joints for cloth, rope and loop. Even though the main joints are included automatically, this sub-element is still useful for adjusting their attributes.

The **twist** kind corresponds to hinge joints enabling rope, loop and cloth objects to twist. These are optional joints and are only created if this sub-element is present. This sub-element is also used to adjust the attributes of the optional twist joints. For other composite object types this sub-element has no effect.

The **stretch** kind corresponds to slide joints enabling rope, loop and cloth objects to stretch. These are optional joints and are only created if this sub-element is present. This sub-element is also used to adjust the attributes of the optional stretch joints. For other composite object types this sub-element has no effect.

The **particle** kind can only be used with the particle composite type. As opposed to all previous kinds, this kind *replaces* the default 3 sliders with user-defined joints. User-defined joints can be repeated, for example to create planar particles with two sliders and a hinge.

solreffix, **solimpfix**

These are the solref and solimp attributes used to equality-constrain the joint. Whether or not a given joint is quality-constrained depends on the joint kind and composite object type as explained above. For joints that are not equality-constrained, this attribute has no effect. The defaults are adjusted depending on the composite type. Otherwise these attributes obey the same rules as all othe [illegible] limp attributes in MJCF. See Solver parameters.

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group, **stiffness**, **damping**, **armature**, **limited**, **range**, **margin**, **solreflimit**, **solimplimit**, **frictionloss**, **solreffriction**, **solimpfriction**, **type**

Same meaning as regular joint attributes.

body/composite/ tendon (*)

Tendons are treated similarly to joints in composite objects. The tendon kind specified here together with the composite body type imply the tendon type as used in the rest of MJCF. This sub-element is used to both create optional tendons, and adjust the attributes of automatic and optional tendons. One difference from joints is that all tendons used in composite objects are equality-constrained.

kind: [main, shear], required

The **main** kind corresponds to tendons holding the composite body together. These are the spatial tendons that connect neighboring bodies in grid and cloth, and the fixed tendon used to preserve the volume of box, cylinder and ellipsoid. For other composite types this sub-element has no effect.

The **shear** kind corresponds to diagonal tendons that prevent shear (as opposed to enabling - which is the function of optional joints). Such tendons can be created in 2D grid objects and cloth objects. For all other composite object types this sub-element has no effect.

solreffix, **solimpfix**

These are the solref and solimp attributes used to equality-constrain the tendon. The defaults are adjusted depending on the composite type. Otherwise these attributes obey the same rules as all other solref and solimp attributes in MJCF. See Solver parameters.

group, **stiffness**, **damping**, **limited**, **range**, **margin**, **solreflimit**, **solimplimit**, **frictionloss**, **solreffriction**, **solimpfriction**, **material**, **rgba**, **width**

Same meaning as regular tendon attributes.

body/composite/ geom (?)

This sub-element adjusts the attributes of the geoms in the composite object. The default attributes are the same as in the rest of MJCF (except that user-defined defaults have no effect here). Note that the geom sub-element can appears only once, unlike joint and tendon sub-elements which can appear multiple times. This is because different kinds of joints and tendons have different sets of attributes, while all geoms in the composite object are identical.

type, **contype**, **conaffinity**, **condim**, **group**, **priority**, **size**, **material**, **rgba**, **friction**, **mass**, **density**, **solmix**, **solref**, **solimp**, **margin**, **gap**

Same meaning as regular geom attributes.

body/composite/ site (?)

This sub-element adjusts the attributes of the sites in the composite object. Otherwise it is the same as geom above.

group, **size**, **material**, **rgba**

Same meaning as regular site attributes.

body/composite/ skin (?)

If this element is included, the model compiler will generate a skinned mesh asset and attach it to the element bodies of the composite object. Skin can be attached to 2D grid, cloth, box, cylinder and ellipsoid. For other composite types it has no effect. Note that the skin created here is equivalent to a skin specified directly in the XML, as opposed to a skin loaded from file. So if the model is saved as XML, it will contain a large section describing the automatically-generated skin.

texcoord: [false, true], "false"

If this is true, explicit texture coordinates will be generated, mapping the skin to the unit square in texture space. This is needed when the material specifies a texture. If texcoord is false and the skin has texture, the texture will appear fixed to the world instead of the skin. The reason for having this attribute in the first place is because skins with texture coordinates upload these coordinates to the GPU even if no texture is applied later. So this attribute should be set to false in cases where no texture will be applied via the material attribute.

material, **rgba**

Same meaning as in geom.

inflate: real, "0"

The default value of 0 means that the automatically-generated skin passes through the centers of the body elements comprising the composite object. Positive values offset each skin vertex by the specified amount, in the direction normal to the (non-inflated) skin at that vertex. This has two uses. First, in 2D objects, a small positive inflate factor is needed to avoid aliasing artifacts. Second, collisions are done with geoms that create some thickness, even for 2D objects. Inflating the skin with a value equal to the geom size will render the skin as a "mattress" that better represents the actual collision geometry. The value of this attribute is copied into the corresponding attribute of the **skin** asset being created.

subgrid: int, "0"

This is only applicable to cloth and 2D grid types, and has no effect for any other composite type. The default value of 0 means that the skin has as many vertices as the number of element bodies. A positive value causes subdivision, with the specified number of (additional) grid lines. In this case the model compiler generates a denser skin using bi-cubic interpolation. This increases the quality of the rendering (especially in the absence of textures) but also slows down the renderer, so use it with caution. Values above 3 are unlikely to be needed.

body/composite/ pin (*)

This sub-element can be used to pin some of the element bodies in grid objects (both 1D and 2D). Pinning means that the corresponding body has no joints, and therefore it is rigidly fixed to the parent body. When the parent is the world, this has the effect of hanging a string or a cloth in space. If the parent body is moving, this can be used to model a handle where the composite object is attached. For other composite types this sub-element has no effect.

coord: int(2), required

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The grid coordinates k body which should be pinned. The coordinates are zero-based. For 1D grids this attribute can have only one number, in which case the second number is automatically set to 0.

contact (*)

This is a grouping element and does not have any attributes. It groups elements that are used to adjust the generation of candidate contact pairs for collision checking. Collision detection was described in detail in the Computation chapter, thus the description here is brief.

contact/ pair (*)

This element creates a predefined geom pair, which will be checked for collision if the collision attribute of option is set to “all” or “predefined”. Unlike dynamically generated pairs whose properties are inferred from the corresponding geom properties, the pairs created here specify all their properties explicitly or through defaults, and the properties of the individual geoms are not used. Anisotropic friction can only be created with this element.

name: string, optional

Name of this contact pair.

class: string, optional

Defaults class for setting unspecified attributes.

geom1: string, required

The name of the first geom in the pair.

geom2: string, required

The name of the second geom in the pair. The contact force vector computed by the solver and stored in mjData.efc_force points from the first towards the second geom by convention. The forces applied to the system are of course equal and opposite, so the order of geoms does not affect the physics.

condim: int, “3”

The dimensionality of the contacts generated by this geom pair.

friction: real(5), “1 1 0.005 0.0001 0.0001”

The friction coefficients of the contacts generated by this geom pair. Making the first two coefficients different results in anisotropic tangential friction. Making the last two coefficients different results in anisotropic rolling friction. The length of this array is not enforced by the parser, and can be smaller than 5. This is because some of the coefficients may not be used, depending on the contact dimensionality. Unspecified coefficients remain equal to their defaults.

solref, solimp

Constraint solver parameters for contact simulation. See Solver parameters.

margin: real, “0”

Distance threshold below which contacts are detected and included in the global array mjData.contact.

gap: real, “0”

This attribute is used to enable the generation of inactive contacts, i.e., contacts that are ignored by the constraint solver but are included in mjData.contact for the purpose of custom computations. When this value is positive, geom distances between margin and margin-gap correspond to such inactive contacts.

contact/ exclude (*)

This element is used to exclude a pair of bodies from collision checking. Unlike all other contact-related elements which refer to geoms, this element refers to bodies. Experience has shown that exclusion is more useful on the level of bodies. The collision between any geom defined in the first body and any geom defined in the second body is excluded. The exclusion rules defined here are applied only when the collision attribute of option is set to “all” or “dynamic”. Setting this attribute to “predefined” disables the exclusion mechanism and the geom pairs defined with the pair element above are checked for collisions.

name: string, optional

Name of this exclude pair.

body1: string, required

The name of the first body in the pair.

body2: string, required

The name of the second body in the pair.

equality (*)

This is a grouping element for equality constraints. It does not have attributes. See the Equality section of the Computation chapter for a detailed description of equality constraints. Several attributes are common to all equality constraint types, thus we document them only once, under the connect element.

equality/ connect (*)

This element creates an equality constraint that connects two bodies at a point. The point is not necessarily within the geoms volumes of either body. This constraint can be used to define ball joints outside the kinematic tree.

name: string, optional

Name of the equality constraint.

class: string, optional

Defaults class for setting unspecified attributes.

active: [false, true], “true”

If this attribute is set to “true”, the constraint is active and the constraint solver will try to enforce it. The corresponding field in mjModel is mjData.eq_active. This field can be used at runtime to turn specific constraints on an off.

solref, **solimp**

Constraint solver par[illegible]uality constraint simulation. See Solver parameters.

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body1: string, required

Name of the first body participating in the constraint.

body2: string, optional

Name of the second body participating in the constraint. If this attribute is omitted, the second body is the world body.

anchor: real(3), required

Coordinates of the 3D anchor point where the two bodies are connected. In the compiled mjModel the anchor is stored twice, relative to the local frame of each body. At runtime this yields two global points computed by forward kinematics; the constraint solver pushes these points towards each other. In the MJCF model however only one point is given. We assume that the equality constraint is exactly satisfied in the configuration in which the model is defined (this applies to all other constraint types as well). The compiler uses the single anchor specified in the MJCF model to compute the two body-relative anchor points in mjModel. If the MJCF model is in global coordinates, as determined by the coordinate attribute of compiler, the anchor is specified in global coordinates. Otherwise the anchor is specified relative to the local coordinate frame of the *first* body.

equality/ weld (*)

This element creates a weld equality constraint. It attaches two bodies to each other, removing all relative degrees of freedom between them (softly of course, like all other constraints in MuJoCo). The two bodies are not required to be close to each other. The relative body position and orientation being enforced by the constraint solver is the one in which the model was defined. Note that two bodies can also be welded together rigidly, by defining one body as a child of the other body, without any joint elements in the child body.

name, **class**, **active**, **solref**, **solimp**

Same as in connect element.

body1: string, required

Name of the first body.

body2: string, optional

Name of the second body. If this attribute is omitted, the second body is the world body. Welding a body to the world and changing the corresponding component of mjModel.eq_active at runtime can be used to fix the body temporarily.

relpose: real(7), "0 1 0 0 0 0 0"

This attribute specifies the relative pose (3D position followed by 4D quaternion orientation) of body2 relative to body1. If the quaternion part (i.e., last 4 components of the vector) are all zeros, as in the default setting, this attribute is ignored and the relative pose is the one corresponding to the model reference pose in qpos0. The unusual default is because all equality constraint types share the same default for their numeric parameters.

anchor: real(3), "0 0 0"

Coordinates of the weld point relative to body2. If relpose is not specified, the meaning of this parameter is the same as for connect constraints, except that is relative to body2. If relpose is specified, body1 will use the pose to compute its anchor point.

torquescale: real, "1"

Relative torque-to-force ratio. This ratio is used by the weld to scale how much it "cares" about rotational displacements vs. translational displacements. Setting this value to 0 makes the **weld** behave like a **connect** constraint. Note that this value has units of length and can therefore be interpreted as follows. Imagining that the weld is implemented by a patch of glue sticking the two bodies together, torquescale can be interpreted as the diameter of this glue patch.

equality/ joint (*)

This element constrains the position or angle of one joint to be a quartic polynomial of another joint. Only scalar joint types (slide and hinge) can be used.

name, **class**, **active**, **solref**, **solimp**

Same as in connect element.

joint1: string, required

Name of the first joint.

joint2: string, optional

Name of the second joint. If this attribute is omitted, the first joint is fixed to a constant.

polycoef: real(5), "0 1 0 0 0"

Coefficients a0 … a4 of the quartic polynomial. If the two joint values are y and x, and their reference positions (corresponding to the joint values in the initial model configuration) are y0 and x0, the constraint is: y-y0 = a0 + a1*(x-x0) + a2*(x-x0)^2 + a3*(x-x0)^3 + a4*(x-x0)^4 Omitting the second joint is equivalent to setting x = x0, in which case the constraint is y = y0 + a0.

equality/ tendon (*)

This element constrains the length of one tendon to be a quartic polynomial of another tendon.

name, **class**, **active**, **solref**, **solimp**

Same as in connect element.

tendon1: string, required

Name of the first tendon.

tendon2: string, optional

Name of the second tendon. If this attribute is omitted, the first tendon is fixed to a constant.

polycoef: real(5), "0 1 0 0 0"

Same as in the equality/ joint element above, but applied to tendon lengths instead of joint positions.

equality/ distance (*)

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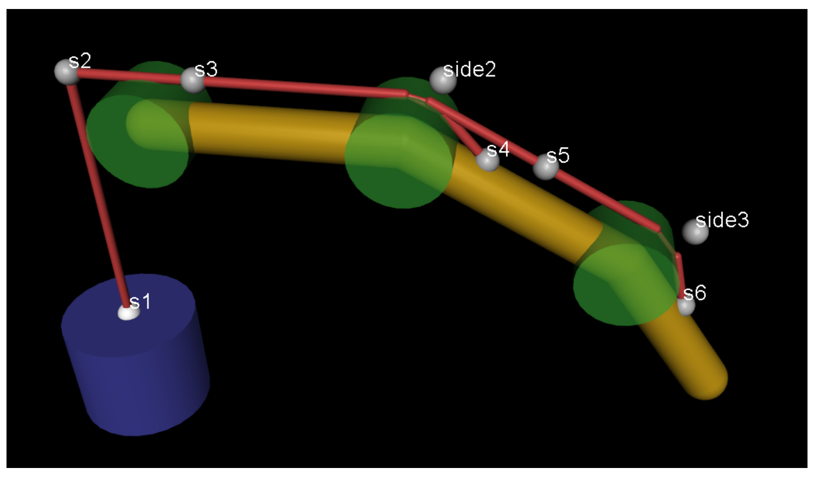
Distance equality constrai ved in MuJoCo version 2.2.2. If you are using an earlier version, please switch to the corresponding version of the documentation.

tendon (*)

Grouping element for tendon definitions. The attributes of fixed tendons are a subset of the attributes of spatial tendons, thus we document them only once under spatial tendons. Tendons can be used to impose length limits, simulate spring, damping and dry friction forces, as well as attach actuators to them. When used in equality constraints, tendons can also represent different forms of mechanical coupling.

tendon/ spatial (*)



This element creates a spatial tendon, which is a minimum-length path passing through specified via-points and wrapping around specified obstacle geoms. The objects along the path are defined with the sub-elements site and geom below. One can also define pulleys which split the path in multiple branches. Each branch of the tendon path must start and end with a site, and if it has multiple obstacle geoms they must be separated by sites - so as to avoid the need for an iterative solver at the tendon level. This example illustrates a multi-branch tendon acting as a finger extensor, with a counter-weight instead of an actuator.

MuJoCo 2.0 introduced a second form of wrapping, where the tendon is constrained to pass through a geom rather than wrap around it. This is enabled automatically when a sidesite is specified and its position is inside the volume of the obstacle geom.

tendon.xml

name: string, optional

Name of the tendon.

class: string, optional

Defaults class for setting unspecified attributes.

group: int, "0"

Integer group to which the tendon belongs. This attribute can be used for custom tags. It is also used by the visualizer to enable and disable the rendering of entire groups of tendons.

limited: [false, true, auto], "auto"

If this attribute is "true", the length limits defined by the range attribute below are imposed by the constraint solver. If this attribute is "auto", and autolimits is set in compiler, length limits will be enabled if range is defined.

range: real(2), "0 0"

Range of allowed tendon lengths. Setting this attribute without specifying limited is an error, unless autolimits is set in compiler.

solreflimit, **solimplimit**

Constraint solver parameters for simulating tendon limits. See Solver parameters.

solreffriction, **solimpfriction**

Constraint solver parameters for simulating dry friction in the tendon. See Solver parameters.

margin: real, "0"

The limit constraint becomes active when the absolute value of the difference between the tendon length and either limit of the specified range falls below this margin. Similar to contacts, the margin parameter is subtracted from the difference between the range limit and the tendon length. The resulting constraint distance is always negative when the constraint is active. This quantity is used to compute constraint impedance as a function of distance, as explained in Solver parameters.

frictionloss: real, "0"

Friction loss caused by dry friction. To enable friction loss, set this attribute to a positive value.

width: real, "0.003"

Radius of the cross-section area of the spatial tendon, used for rendering. Parts of the tendon that wrap around geom obstacles are rendered with reduced width.

material: string, optional

Material used to set the appearance of the tendon.

rgba: real(4), "0.5 0.5 0.5 1"

Color and transparency of the tendon. When this value is different from the internal default, it overrides the corresponding material properties.

springlength: real(2), "-1 -1"

Spring resting position, can take either one or two values. If one value is given, it corresponds to the length of the tendon at rest. If it is `-1`, the tendon resting length is determined from the model reference configuration in `mjModel.qpos0`.
Note that the default value of `-1`, which invokes the automatic length computation, was designed with spatial tendons in mind, which can only have nonegative length. In order to set the springlength of a fixed tendon to `-1`, use a nearby value like `-0.99999`.
If two non-decreasing values are given, they define a dead-band range. If the tendon length is between the two values, the force is 0. If it is outside this range, the force behaves like a regular spring, with the rest-point corresponding to the nearest springlength value. A deadband can be used to define tendons whose limits are enforced by springs rather than constraints.

stiffness: real, "0"

Stiffness coefficient. A positive value generates a spring force (linear in position) acting along the tendon.

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damping: real, "0"

Damping coefficient. A positive value generates a damping force (linear in velocity) acting along the tendon. Unlike joint damping which is integrated implicitly by the Euler method, tendon damping is not integrated implicitly, thus joint damping should be used if possible.

user: real(nuser_tendon), "0 0 ..."

See User parameters.

tendon/spatial/ site (*)

This attribute specifies a site that the tendon path has to pass through. Recall that sites are rigidly attached to bodies.

site: string, required

The name of the site that the tendon must pass through.

tendon/spatial/ geom (*)

This element specifies a geom that acts as an obstacle for the tendon path. If the minimum-length path does not touch the geom it has no effect; otherwise the path wraps around the surface of the geom. Wrapping is computed analytically, which is why we restrict the geom types allowed here to spheres and cylinders. The latter are treated as having infinite length for tendon wrapping purposes. If a sidesite is defined, and its position is inside the geom, then the tendon is constrained to pass through the geom instead of passing around it.

geom: string, required

The name of a geom that acts as an obstacle for the tendon path. Only sphere and cylinder geoms can be referenced here.

sidesite: string, optional

To prevent the tendon path from snapping from one side of the geom to the other as the model configuration varies, the user can define a preferred "side" of the geom. At runtime, the wrap that is closer to the specified site is automatically selected. Specifying a side site is often needed in practice. If the side site is inside the geom, the tendon is constrained to pass through the interior of the geom.

tendon/spatial/ pulley (*)

This element starts a new branch in the tendon path. The branches are not required to be connected spatially. Similar to the transmissions described in the Actuation model section of the Computation chapter, the quantity that affects the simulation is the tendon length and its gradient with respect to the joint positions. If a spatial tendon has multiple branches, the length of each branch is divided by the divisor attribute of the pulley element that started the branch, and added up to obtain the overall tendon length. This is why the spatial relations among branches are not relevant to the simulation. The tendon.xml example above illustrated the use of pulleys.

divisor: real, required

The length of the tendon branch started by the pulley element is divided by the value specified here. For a physical pulley that splits a single branch into two parallel branches, the common branch would have divisor value of 1 and the two branches following the pulley would have divisor values of 2. If one of them is further split by another pulley, each new branch would have divisor value of 4 and so on. Note that in MJCF each branch starts with a pulley, thus a single physical pulley is modeled with two MJCF pulleys. If no pulley elements are included in the tendon path, the first and only branch has divisor value of 1.

tendon/ fixed (*)

This element creates an abstract tendon whose length is defined as a linear combination of joint positions. Recall that the tendon length and its gradient are the only quantities needed for simulation. Thus we could define any scalar function of joint positions, call it "tendon", and plug it in MuJoCo. Presently the only such function is a fixed linear combination. The attributes of fixed tendons are a subset of the attributes of spatial tendons and have the same meaning as above.

name, **class**, **group**, **limited**, **range**, **solreflimit**, **solimplimit**, **solreffriction**, **solimpfriction**, **frictionloss**, **margin**, **springlength**, **stiffness**, **damping**, **user**

Same as in the spatial element.

tendon/fixed/ joint (*)

This element adds a joint to the computation of the fixed tendon length. The position or angle of each included joint is multiplied by the corresponding coef value, and added up to obtain the tendon length.

joint: string, required

Name of the joint to be added to the fixed tendon. Only scalar joints (slide and hinge) can be referenced here.

coef: real, required

Scalar coefficient multiplying the position or angle of the specified joint.

actuator (*)

This is a grouping element for actuator definitions. Recall the discussion of MuJoCo's Actuation model in the Computation chapter, and the Actuator shortcuts discussed earlier in this chapter. The first 13 attributes of all actuator-related elements below are the same, so we document them only once, under the **general** actuator.

actuator/ general (*)

This element creates a general actuator, providing full access to all actuator components and allowing the user to specify them independently.

name: string, optional

Element name. See Naming elements.

class: string, optional

Active defaults class. See Default settings.

group: int, "0"

Integer group to whic ↑ Back to top belongs. This attribute can be used for custom tags. It is also used by the visualizer to enable and disable the rendering of entire groups of actuators.

ctrllimited: [false, true, auto], "auto"

If true, the control input to this actuator is automatically clamped to ctrlrange at runtime. If false, control input clamping is disabled. If "auto" and autolimits is set in compiler, control clamping will automatically be set to true if ctrlrange is defined without explicitly setting this attribute to "true". Note that control input clamping can also be globally disabled with the clampctrl attribute of option/flag.

forcelimited: [false, true, auto], "auto"

If true, the force output of this actuator is automatically clamped to forcerange at runtime. If false, force clamping is disabled. If "auto" and autolimits is set in compiler, force clamping will automatically be set to true if forcerange is defined without explicitly setting this attribute to "true".

actlimited: [false, true, auto], "auto"

If true, the internal state (activation) associated with this actuator is automatically clamped to actrange at runtime. If false, activation clamping is disabled. If "auto" and autolimits is set in compiler, activation clamping will automatically be set to true if actrange is defined without explicitly setting this attribute to "true". See the Activation clamping section for more details.

ctrlrange: real(2), "0 0"

Range for clamping the control input. The compiler expects the first value to be smaller than the second value.
Setting this attribute without specifying ctrllimited is an error, unless autolimits is set in compiler.

forcerange: real(2), "0 0"

Range for clamping the force output. The compiler expects the first value to be no greater than the second value.
Setting this attribute without specifying forcelimited is an error, unless autolimits is set in compiler.

actrange: real(2), "0 0"

Range for clamping the activation state. The compiler expects the first value to be no greater than the second value. See the Activation clamping section for more details.
Setting this attribute without specifying actlimited is an error, unless autolimits is set in compiler.

lengthrange: real(2), "0 0"

Range of feasible lengths of the actuator's transmission. See Length Range.

gear: real(6), "1 0 0 0 0 0"

This attribute scales the length (and consequently moment arms, velocity and force) of the actuator, for all transmission types. It is different from the gain in the force generation mechanism, because the gain only scales the force output and does not affect the length, moment arms and velocity. For actuators with scalar transmission, only the first element of this vector is used. The remaining elements are needed for joint, jointinparent and site transmissions where this attribute is used to specify 3D force and torque axes.

cranklength: real, "0"

Used only for the slider-crank transmission type. Specifies the length of the connecting rod. The compiler expects this value to be positive when a slider-crank transmission is present.

joint: string, optional

This and the next four attributes determine the type of actuator transmission. All of them are optional, and exactly one of them must be specified. If this attribute is specified, the actuator acts on the given joint. For **hinge** and **slide** joints, the actuator length equals the joint position/angle times the first element of gear. For **ball** joints, the first three elements of gear define a 3d rotation axis in the child frame around which the actuator produces torque. The actuator length is defined as the dot-product between this gear axis and the angle-axis representation of the joint quaternion, and is in units of radian if gear is normalized (generally scaled by by the norm of gear). Note that after total rotation of more than π, the length will wrap to $-\pi$, and vice-versa. Therefore **position** servos for ball joints should generally use tighter limits which prevent this wrapping. For **free** joints, gear defines a 3d translation axis in the world frame followed by a 3d rotation axis in the child frame. The actuator generates force and torque relative to the specified axes. The actuator length for free joints is defined as zero (so it should not be used with position servos).

jointinparent: string, optional

Identical to joint, except that for ball and free joints, the 3d rotation axis given by gear is defined in the parent frame (which is the world frame for free joints) rather than the child frame.

site: string, optional

This transmission can apply force and torque at a site. The gear vector defines a 3d translation axis followed by a 3d rotation axis. Both are defined in the site's frame. This can be used to model jets and propellers. The effect is similar to actuating a free joint, and the actuator length is defined as zero unless a refsite is defined (see below). One difference from the joint and jointinparent transmissions above is that here the actuator operates on a site rather than a joint, but this difference disappears when the site is defined at the frame origin of the free-floating body. The other difference is that for site transmissions both the translation and rotation axes are defined in local coordinates. In contrast, translation is global and rotation is local for joint, and both translation and rotation are global for jointinparent.

refsite: string, optional

When using a site transmission, measure the translation and rotation w.r.t the frame of the refsite. In this case the actuator *does* have length and **position** actuators can be used to directly control an end effector, see refsite.xml example model. As above, the length is the dot product of the gear vector and the frame difference. So `gear="0 1 0 0 0`

`0"` means "Y-offset of site in the refsite frame", while `gear="0 0 0 0 0 1"` means rotation "Z-rotation of site in the It is recommended to use a normalized gear vector with nonzeros in only the first 3 *or* the last 3 elements of gear, so the actuator length will be in either length units or radians, respectively. As with ball joints (see joint above), for rotations which exceed a total angle of π will wrap around, so tighter limits are recommended.

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body: string, optional

This transmission can apply linear forces at contact points in the direction of the contact normal. The set of contacts is all those belonging to the specified body. This can be used to model natural active adhesion mechanisms like the feet of geckos and insects. The actuator length is again defined as zero. For more information, see the adhesion shortcut below.

tendon: string, optional

If specified, the actuator acts on the given tendon. The actuator length equals the tendon length times the gear ratio. Both spatial and fixed tendons can be used.

cranksite: string, optional

If specified, the actuator acts on a slider-crank mechanism which is implicitly determined by the actuator (i.e., it is not a separate model element). The specified site corresponds to the pin joining the crank and the connecting rod. The actuator length equals the position of the slider-crank mechanism times the gear ratio.

slidersite: string, required for slider-crank transmission

Used only for the slider-crank transmission type. The specified site is the pin joining the slider and the connecting rod. The slider moves along the z-axis of the slidersite frame. Therefore the site should be oriented as needed when it is defined in the kinematic tree; its orientation cannot be changed in the actuator definition.

user: real(nuser_actuator), "0 ... 0"

See User parameters.

actdim: real, "-1"

Dimension of the activation state. The default value of `-1` instructs the compiler to set the dimension according to the dyntype. Values larger than `1` are only allowed for user-defined activation dynamics, as native types require dimensions of only 0 or 1. For activation dimensions bigger than 1, the *last element* is used to generate force.

dyntype: [none, integrator, filter, muscle, user], "none"

Activation dynamics type for the actuator. The available dynamics types were already described in the Actuation model section. Repeating that description in somewhat different notation (corresponding to the mjModel and mjData fields involved) we have:

Keyword	Description
none	No internal state
integrator	act_dot = ctrl
filter	act_dot = (ctrl - act) / dynprm[0]
muscle	act_dot = mju_muscleDynamics(...)
user	act_dot = mjcb_act_dyn(...)

gaintype: [fixed, muscle, user], "fixed"

The gain and bias together determine the output of the force generation mechanism, which is currently assumed to be affine. As already explained in Actuation model, the general formula is: scalar_force = gain_term * (act or ctrl) + bias_term. The formula uses the activation state when present, and the control otherwise. The keywords have the following meaning:

Keyword	Description
fixed	gain_term = gainprm[0]
muscle	gain_term = mju_muscleGain(...)
user	gain_term = mjcb_act_gain(...)

biastype: [none, affine, muscle, user], "none"

The keywords have the following meaning:

Keyword	Description
none	bias_term = 0
affine	bias_term = biasprm[0] + biasprm[1]*length + biasprm[2]*velocity
muscle	bias_term = mju_muscleBias(...)
user	bias_term = mjcb_act_bias(...)

dynprm: real(10), "1 0 ... 0"

Activation dynamics parameters. The built-in activation types (except for muscle) use only the first parameter, but we provide additional parameters in case user callbacks implement a more elaborate model. The length of this array is not enforced by the parser, so the user can enter as many parameters as needed. These defaults are not compatible with muscle actuators; see muscle below.

gainprm: real(10), "1 0 ... 0"

Gain parameters. The built-in gain types (except for muscle) use only the first parameter, but we provide additional parameters in case user callbacks implement a more elaborate model. The length of this array is not enforced by the parser, so the user can enter as many parameters as needed. These defaults are not compatible with muscle actuators; see muscle below.

biasprm: real(10), "0 ... 0"

Bias parameters. The affine bias type uses three parameters. The length of this array is not enforced by the parser, so the user can enter as many parameters as needed. These defaults are not compatible with muscle actuators; see muscle below.

actuator/ motor (*)

This and the next three elements are the Actuator shortcuts discussed earlier. When a such shortcut is encountered, t ↑ Back to top es a **general** actuator and sets its dynprm, gainprm and biasprm attributes to the internal defaults shown above, regardless of any default settings. It then adjusts dyntype, gaintype and biastype depending on the shortcut, parses any custom attributes (beyond the common ones), and translates them into regular attributes (i.e., attributes of the **general** actuator type) as explained here.

This element creates a direct-drive actuator. The underlying **general** attributes are set as follows:

Attribute	Setting	Attribute	Setting
dyntype	none	dynprm	1 0 0
gaintype	fixed	gainprm	1 0 0
biastype	none	biasprm	0 0 0

This element does not have custom attributes. It only has common attributes, which are:

name, **class**, **group**, **ctrllimited**, **forcelimited**, **ctrlrange**, **forcerange**, **lengthrange**, **gear**, **cranklength**, **joint**, **jointinparent**, **tendon**, **cranksite**, **slidersite**, **site**, **user**

Same as in actuator/ general.

actuator/ position (*)

This element creates a position servo. The underlying **general** attributes are set as follows:

Attribute	Setting	Attribute	Setting
dyntype	none	dynprm	1 0 0
gaintype	fixed	gainprm	kp 0 0
biastype	affine	biasprm	0 -kp 0

This element has one custom attribute in addition to the common attributes:

name, **class**, **group**, **ctrllimited**, **forcelimited**, **ctrlrange**, **forcerange**, **lengthrange**, **gear**, **cranklength**, **joint**, **jointinparent**, **tendon**, **cranksite**, **slidersite**, **site**, **user**

Same as in actuator/ general.

kp: real, "1"

Position feedback gain.

actuator/ velocity (*)

This element creates a velocity servo. Note that in order create a PD controller, one has to define two actuators: a position servo and a velocity servo. This is because MuJoCo actuators are SISO while a PD controller takes two control inputs (reference position and reference velocity). The underlying **general** attributes are set as follows:

Attribute	Setting	Attribute	Setting
dyntype	none	dynprm	1 0 0
gaintype	fixed	gainprm	kv 0 0
biastype	affine	biasprm	0 0 -kv

This element has one custom attribute in addition to the common attributes:

name, **class**, **group**, **ctrllimited**, **forcelimited**, **ctrlrange**, **forcerange**, **lengthrange**, **gear**, **cranklength**, **joint**, **jointinparent**, **tendon**, **cranksite**, **slidersite**, **site**, **user**

Same as in actuator/ general.

kv: real, "1"

Velocity feedback gain.

actuator/ intvelocity (*)

This element creates an integrated-velocity servo. For more information, see the Activation clamping section of the Modeling chapter. The underlying **general** attributes are set as follows:

Attribute	Setting	Attribute	Setting
dyntype	integrator	dynprm	1 0 0
gaintype	fixed	gainprm	kp 0 0
biastype	affine	biasprm	0 -kp 0
actlimited	true		

This element has one custom attribute in addition to the common attributes:

name, **class**, **group**, **ctrllimited**, **forcelimited**, **ctrlrange**, **forcerange**, **lengthrange**, **gear**, **cranklength**, **joint**, **jointinparent**, **tendon**, **cranksite**, **slidersite**, **site**, **user**

Same as in actuator/ general.

kp: real, "1"

Position feedback gain.

actuator/ damper (*)

This element is an active damper which produces a force proportional to both velocity and control: `F = - kv * velocity * control`, where `kv` must be nonnegative. ctrlrange is required and must also be nonnegative. The underlying **general** attributes are set as follows:

Attribute	Setting	Attribute	Setting
dyntype	none	dynprm	1 0 0
gaintype	affine	gainprm	0 0 -kv
biastype	none	biasprm	0 0 0

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Attribute	Setting	Attribute	Setting
ctrllimited	true		

This element has one custom attribute in addition to the common attributes:

name, **class**, **group**, **ctrllimited**, **forcelimited**, **ctrlrange**, **forcerange**, **lengthrange**, **gear**, **cranklength**, **joint**, **jointinparent**, **tendon**, **cranksite**, **slidersite**, **site**, **user**

Same as in actuator/ general.

kv: real, "1"

Velocity feedback gain.

actuator/ cylinder (*)

This element is suitable for modeling pneumatic or hydraulic cylinders. The underlying **general** attributes are set as follows:

Attribute	Setting	Attribute	Setting
dyntype	filter	dynprm	timeconst 0 0
gaintype	fixed	gainprm	area 0 0
biastype	affine	biasprm	bias(3)

This element has four custom attributes in addition to the common attributes:

name, **class**, **group**, **ctrllimited**, **forcelimited**, **ctrlrange**, **forcerange**, **lengthrange**, **gear**, **cranklength**, **joint**, **jointinparent**, **tendon**, **cranksite**, **slidersite**, **site**, **user**

Same as in actuator/ general.

timeconst: real, "1"

Time constant of the activation dynamics.

area: real, "1"

Area of the cylinder. This is used internally as actuator gain.

diameter: real, optional

Instead of area the user can specify diameter. If both are specified, diameter has precedence.

bias: real(3), "0 0 0"

Bias parameters, copied internally into biasprm.

actuator/ muscle (*)

This element is used to model a muscle actuator, as described in the Muscles actuators section. The underlying **general** attributes are set as follows:

Attribute	Setting	Attribute	Setting
dyntype	muscle	dynprm	timeconst(2)
gaintype	muscle	gainprm	range(2), force, scale, lmin, lmax, vmax, fpmax, fvmax
biastype	muscle	biasprm	same as gainprm

This element has nine custom attributes in addition to the common attributes:

name, **class**, **group**, **ctrllimited**, **forcelimited**, **ctrlrange**, **forcerange**, **lengthrange**, **gear**, **cranklength**, **joint**, **jointinparent**, **tendon**, **cranksite**, **slidersite**, **user**

Same as in actuator/ general.

timeconst: real(2), "0.01 0.04"

Time constants for activation and de-activation dynamics.

range: real(2), "0.75 1.05"

Operating length range of the muscle, in units of L0.

force: real, "-1"

Peak active force at rest. If this value is negative, the peak force is determined automatically using the scale attribute below.

scale: real, "200"

If the force attribute is negative, the peak active force for the muscle is set to this value divided by mjModel.actuator_acc0. The latter is the norm of the joint-space acceleration vector caused by unit force on the actuator's transmission in qpos0. In other words, scaling produces higher peak forces for muscles that pull more weight.

lmin: real, "0.5"

Lower position range of the normalized FLV curve, in units of L0.

lmax: real, "1.6"

Upper position range of the normalized FLV curve, in units of L0.

vmax: real, "1.5"

Shortening velocity at which muscle force drops to zero, in units of L0 per second.

fpmax: real, "1.3"

Passive force generated at lmax, relative to the peak rest force.

fvmax: real, "1.2"

Active force generated at saturating lengthening velocity, relative to the peak rest force.

actuator/ adhesion (*)

This element defines an active adhesion actuator which injects forces at contacts in the normal direction, see illustration video. The model shown in the video can be found here and includes inline annotations. The transmission target is a **body**, and adhesive forces are injected into all contacts involving geoms which belong to this body. The force is divided equally between multiple contacts. When the gap attribute is not used, this actuator

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requires active contacts and cannot apply a force at a distance, more like the act n the feet of geckos and insects rather than an industrial vacuum gripper. In order to enable “suction at a distance”, “inflate” the body’s geoms by margin and add a corresponding gap which activates contacts only after gap penetration distance. This will create a layer around the geom where contacts are detected but are inactive, and can be used for applying the adhesive force. In the video above, such inactive contacts are blue, while active contacts are orange. An adhesion actuator’s length is always 0. ctrlrange is required and must also be nonnegative (no repulsive forces are allowed). The underlying **general** attributes are set as follows:

Attribute	Setting	Attribute	Setting
dyntype	none	dynprm	1 0 0
gaintype	fixed	gainprm	gain 0 0
biastype	none	biasprm	0 0 0
trntype	body	ctrllimited	true

This element has a subset of the common attributes and two custom attributes.

name, **class**, **group**, **forcelimited**, **ctrlrange**, **forcerange**, **user**

Same as in actuator/ general.

body: string, required

The actuator acts on all contacts involving this body’s geoms.

gain: real, “1”

Gain of the adhesion actuator, in units of force. The total adhesion force applied by the actuator is the control value multiplied by the gain. This force is distributed equally between all the contacts involving geoms belonging to the target body.

sensor (*)

This is a grouping element for sensor definitions. It does not have attributes. The outputs of all sensors are concatenated in the field mjData.sensordata which has size mjModel.nsensordata. This data is not used in any internal computations.

In addition to the sensors created with the elements below, the top-level function mj_step computes the quantities mjData.cacc, mjData.cfrc_int and mjData.crfc_ext corresponding to body accelerations and interaction forces. Some of these quantities are used to compute the output of certain sensors (force, acceleration etc.) but even if no such sensors are defined in the model, these quantities themselves are “features” that could be of interest to the user.

sensor/ touch (*)

This element creates a touch sensor. The active sensor zone is defined by a site. If a contact point falls within the site’s volume, and involves a geom attached to the same body as the site, the corresponding contact force is included in the sensor reading. If a contact point falls outside the sensor zone, but the normal ray intersects the sensor zone, it is also included. This re-projection feature is needed because, without it, the contact point may leave the sensor zone from the back (due to soft contacts) and cause an erroneous force reading. The output of this sensor is non-negative scalar. It is computed by adding up the (scalar) normal forces from all included contacts.

name, **noise**, **cutoff**, **user**

See Sensors.

site: string, required

Site defining the active sensor zone.

sensor/ accelerometer (*)

This element creates a 3-axis accelerometer. The sensor is mounted at a site, and has the same position and orientation as the site frame. This sensor outputs three numbers, which are the linear acceleration of the site (including gravity) in local coordinates.

name, **noise**, **cutoff**, **user**

See Sensors.

site: string, required

Site where the sensor is mounted. The accelerometer is centered and aligned with the site local frame.

sensor/ velocimeter (*)

This element creates a 3-axis velocimeter. The sensor is mounted at a site, and has the same position and orientation as the site frame. This sensor outputs three numbers, which are the linear velocity of the site in local coordinates.

name, **noise**, **cutoff**, **user**

See Sensors.

site: string, required

Site where the sensor is mounted. The velocimeter is centered and aligned with the site local frame.

sensor/ gyro (*)

This element creates a 3-axis gyroscope. The sensor is mounted at a site, and has the same position and orientation as the site frame. This sensor outputs three numbers, which are the angular velocity of the site in local coordinates. This sensor is often used in conjunction with an accelerometer mounted at the same site, to simulate an inertial measurement unit (IMU).

name, **noise**, **cutoff**, **user**

See Sensors.

site: string, required

Site where the sensor is mounted. The gyroscope is centered and aligned with the site local frame.

sensor/ force (*)

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This element creates a 3-axis force sensor. The sensor outputs three numbers, which are the interaction force between arent body, expressed in the site frame defining the sensor. The convention is that the site is attached to the child body, and the force points from the child towards the parent. The computation here takes into account all forces acting on the system, including contacts as well as external perturbations. Using this sensor often requires creating a dummy body welded to its parent (i.e., having no joint elements).

name, **noise**, **cutoff**, **user**

> See Sensors.

site: *string, required*

> Site where the sensor is mounted. The measured interaction force is between the body where the site is defined and its parent body, and points from the child towards the parent. The physical sensor being modeled could of course be attached to the parent body, in which case the sensor data would have the opposite sign. Note that each body has a unique parent but can have multiple children, which is why we define this sensor through the child rather than the parent body in the pair.

sensor/ torque (*)

This element creates a 3-axis torque sensor. This is similar to the force sensor above, but measures torque rather than force.

name, **noise**, **cutoff**, **user**

> See Sensors.

site: *string, required*

> Site where the sensor is mounted. The measured interaction torque is between the body where the site is defined and its parent body.

sensor/ magnetometer (*)

This element creates a magnetometer. It measures the magnetic flux at the sensor site position, expressed in the sensor site frame. The output is a 3D vector.

name, **noise**, **cutoff**, **user**

> See Sensors.

site: *string, required*

> The site where the sensor is attached.

sensor/ rangefinder (*)

This element creates a rangefinder. It measures the distance to the nearest geom surface, along the ray defined by the positive Z-axis of the sensor site. If the ray does not intersect any geom surface, the sensor output is -1. If the origin of the ray is inside a geom, the surface is still sensed (but not the inner volume). Geoms attached to the same body as the sensor site are excluded. Invisible geoms, defined as geoms whose rgba (or whose material rgba) has alpha=0, are also excluded. Note however that geoms made invisible in the visualizer by disabling their geom group are not excluded; this is because sensor calculations are independent of the visualizer.

name, **noise**, **cutoff**, **user**

> See Sensors.

site: *string, required*

> The site where the sensor is attached.

sensor/ jointpos (*)

This and the remaining sensor elements do not involve sensor-specific computations. Instead they copy into the array mjData.sensordata quantities that are already computed. This element creates a joint position or angle sensor. It can be attached to scalar joints (slide or hinge). Its output is scalar.

name, **noise**, **cutoff**, **user**

> See Sensors.

joint: *string, required*

> The joint whose position or angle will be sensed. Only scalar joints can be referenced here. The sensor output is copied from mjData.qpos.

sensor/ jointvel (*)

This element creates a joint velocity sensor. It can be attached to scalar joints (slide or hinge). Its output is scalar.

name, **noise**, **cutoff**, **user**

> See Sensors.

joint: *string, required*

> The joint whose velocity will be sensed. Only scalar joints can be referenced here. The sensor output is copied from mjData.qvel.

sensor/ tendonpos (*)

This element creates a tendon length sensor. It can be attached to both spatial and fixed tendons. Its output is scalar.

name, **noise**, **cutoff**, **user**

> See Sensors.

tendon: *string, required*

> The tendon whose length will be sensed. The sensor output is copied from mjData.ten_length.

sensor/ tendonvel (*)

This element creates a tendon velocity sensor. It can be attached to both spatial and fixed tendons. Its output is scalar.

name, **noise**, **cutoff**, **user**

> See Sensors.

tendon: *string, required*

The tendon whose velocity will be sensed. The sensor output is copied from mjData.ten_velocity.

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sensor/ actuatorpos (*)

This element creates an actuator length sensor. Recall that each actuator has a transmission which has length. This sensor can be attached to any actuator. Its output is scalar.

name, **noise**, **cutoff**, **user**
: See Sensors.

actuator: string, required
: The actuator whose transmission's length will be sensed. The sensor output is copied from mjData.actuator_length.

sensor/ actuatorvel (*)

This element creates an actuator velocity sensor. This sensor can be attached to any actuator. Its output is scalar.

name, **noise**, **cutoff**, **user**
: See Sensors.

actuator: string, required
: The actuator whose transmission's velocity will be sensed. The sensor output is copied from mjData.actuator_velocity.

sensor/ actuatorfrc (*)

This element creates an actuator force sensor. The quantity being sensed is the scalar actuator force, not the generalized force contributed by the actuator (the latter is the product of the scalar force and the vector of moment arms determined by the transmission). This sensor can be attached to any actuator. Its output is scalar.

name, **noise**, **cutoff**, **user**
: See Sensors.

actuator: string, required
: The actuator whose scalar force output will be sensed. The sensor output is copied from mjData.actuator_force.

sensor/ ballquat (*)

This element creates a quaternion sensor for a ball joints. It outputs 4 numbers corresponding to a unit quaternion.

name, **noise**, **cutoff**, **user**
: See Sensors.

joint: string, required
: The ball joint whose quaternion is sensed. The sensor output is copied from mjData.qpos.

sensor/ ballangvel (*)

This element creates a ball joint angular velocity sensor. It outputs 3 numbers corresponding to the angular velocity of the joint. The norm of that vector is the rotation speed in rad/s and the direction is the axis around which the rotation takes place.

name, **noise**, **cutoff**, **user**
: See Sensors.

joint: string, required
: The ball joint whose angular velocity is sensed. The sensor output is copied from mjData.qvel.

sensor/ jointlimitpos (*)

This element creates a joint limit sensor for position.

name, **noise**, **cutoff**, **user**
: See Sensors.

joint: string, required
: The joint whose limit is sensed. The sensor output equals mjData.efc_pos - mjData.efc_margin for the corresponding limit constraint. Note that the result is negative if the limit is violated, regardless of which side of the limit is violated. If both sides of the limit are violated simultaneously, only the first component is returned. If there is no violation, the result is 0.

sensor/ jointlimitvel (*)

This element creates a joint limit sensor for velocity.

name, **noise**, **cutoff**, **user**
: See Sensors.

joint: string, required
: The joint whose limit is sensed. The sensor output is copied from mjData.efc_vel. If the joint limit is not violated, the result is 0.

sensor/ jointlimitfrc (*)

This element creates a joint limit sensor for constraint force.

name, **noise**, **cutoff**, **user**
: See Sensors.

joint: string, required
: The joint whose limit is sensed. The sensor output is copied from mjData.efc_force. If the joint limit is not violated, the result is 0.

sensor/ tendonlimitpos (*)

This element creates a tendon limit sensor for position.

name, **noise**, **cutoff**, **user**

See Sensors.

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tendon: string, required

The tendon whose limit is sensed. The sensor output equals mjData.efc_pos – mjData.efc_margin for the corresponding limit constraint. If the tendon limit is not violated, the result is 0.

sensor/ tendonlimitvel (*)

This element creates a tendon limit sensor for velocity.

name, **noise**, **cutoff**, **user**

See Sensors.

tendon: string, required

The tendon whose limit is sensed. The sensor output is copied from mjData.efc_vel. If the tendon limit is not violated, the result is 0.

sensor/ tendonlimitfrc (*)

This element creates a tendon limit sensor for constraint force.

name, **noise**, **cutoff**, **user**

See Sensors.

tendon: string, required

The tendon whose limit is sensed. The sensor output is copied from mjData.efc_force. If the tendon limit is not violated, the result is 0.

sensor/ framepos (*)

This element creates a sensor that returns the 3D position of the spatial frame of the object, in global coordinates or optionally with respect to a given frame-of-reference.

name, **noise**, **cutoff**, **user**

See Sensors.

objtype: [body, xbody, geom, site, camera], required

The type of object to which the sensor is attached. This must be an object type that has a spatial frame. “body” refers to the inertial frame of the body, while “xbody” refers to the regular frame of the body (usually centered at the joint with the parent body).

objname: string, required

The name of the object to which the sensor is attached.

reftype: [body, xbody, geom, site, camera]

The type of object to which the frame-of-reference is attached. The semantics are identical to the objtype attribute. If reftype and refname are given, the sensor values will be measured with respect to this frame. If they are not given, sensor values will be measured with respect to the global frame.

refname: string

The name of the object to which the frame-of-reference is attached.

sensor/ framequat (*)

This element creates a sensor that returns the unit quaternion specifying the orientation of the spatial frame of the object, in global coordinates.

name, **noise**, **cutoff**, **user**

See Sensors.

objtype: [body, xbody, geom, site, camera], required

See framepos sensor.

objname: string, required

See framepos sensor.

reftype: [body, xbody, geom, site, camera]

See framepos sensor.

refname: string

See framepos sensor.

sensor/ framexaxis (*)

This element creates a sensor that returns the 3D unit vector corresponding to the X-axis of the spatial frame of the object, in global coordinates.

name, **noise**, **cutoff**, **user**

See Sensors.

objtype: [body, xbody, geom, site, camera], required

See framepos sensor.

objname: string, required

See framepos sensor.

reftype: [body, xbody, geom, site, camera]

See framepos sensor.

refname: string

See framepos sensor.

sensor/ frameyaxis (*)

This element creates a sensor that returns the 3D unit vector corresponding to the Y-axis of the spatial frame of the object, in global coordinates.

name, **noise**, **cutoff**, **user**

See Sensors.

objtype: [body, xbody, geom, site, camera], required

See framepos sensor.

objname: string, required

See framepos sensor.

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reftype: [body, xbody, geom, site, camera]

See framepos sensor.

refname: string

See framepos sensor.

sensor/ framezaxis (*)

This element creates a sensor that returns the 3D unit vector corresponding to the Z-axis of the spatial frame of the object, in global coordinates.

name, **noise**, **cutoff**, **user**

See Sensors.

objtype: [body, xbody, geom, site, camera], required

See framepos sensor.

objname: string, required

See framepos sensor.

reftype: [body, xbody, geom, site, camera]

See framepos sensor.

refname: string

See framepos sensor.

sensor/ framelinvel (*)

This element creates a sensor that returns the 3D linear velocity of the spatial frame of the object, in global coordinates.

name, **noise**, **cutoff**, **user**

See Sensors.

objtype: [body, xbody, geom, site, camera], required

See framepos sensor.

objname: string, required

See framepos sensor.

reftype: [body, xbody, geom, site, camera]

See framepos sensor.

refname: string

See framepos sensor.

sensor/ frameangvel (*)

This element creates a sensor that returns the 3D angular velocity of the spatial frame of the object, in global coordinates.

name, **noise**, **cutoff**, **user**

See Sensors.

objtype: [body, xbody, geom, site, camera], required

See framepos sensor.

objname: string, required

See framepos sensor.

reftype: [body, xbody, geom, site, camera]

See framepos sensor.

refname: string

See framepos sensor.

sensor/ framelinacc (*)

This element creates a sensor that returns the 3D linear acceleration of the spatial frame of the object, in global coordinates.

name, **noise**, **cutoff**, **user**

See Sensors.

objtype: [body, xbody, geom, site, camera], required

See framepos sensor.

objname: string, required

See framepos sensor.

sensor/ frameangacc (*)

This element creates a sensor that returns the 3D angular acceleration of the spatial frame of the object, in global coordinates.

name, **noise**, **cutoff**, **user**

See Sensors.

objtype: [body, xbody, geom, site, camera], required

See framepos sensor.

objname: string, required

See framepos sensor.

sensor/ subtreecom (*)

This element creates sensor that returns the center of mass of the kinematic subtree rooted at a specified body, in global coordinates.

name, **noise**, **cutoff**, **user**

See Sensors.

body: string, required

Name of the body where the kinematic subtree is rooted.

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sensor/ subtreelinvel (*)

This element creates sensor that returns the linear velocity of the center of mass of the kinematic subtree rooted at a specified body, in global coordinates.

name, **noise**, **cutoff**, **user**

See Sensors.

body: string, required

Name of the body where the kinematic subtree is rooted.

sensor/ subtreeangmom (*)

This element creates sensor that returns the angular momentum around the center of mass of the kinematic subtree rooted at a specified body, in global coordinates.

name, **noise**, **cutoff**, **user**

See Sensors.

body: string, required

Name of the body where the kinematic subtree is rooted.

sensor/ clock (*)

This element creates sensor that returns the simulation time.

name, **noise**, **cutoff**, **user**

See Sensors.

sensor/ user (*)

This element creates a user sensor. MuJoCo does not know how to compute the output of this sensor. Instead the user should install the callback mjcb_sensor which is expected to fill in the sensor data in mjData.sensordata. The specification in the XML is used to allocate space for this sensor, and also determine which MuJoCo object it is attached to and what stage of computation it needs before the data can be computed. Note that the MuJoCo object referenced here can be a tuple, which in turn can reference a custom collection of MuJoCo objects - for example several bodies whose center of mass is of interest.

name, **noise**, **cutoff**, **user**

See Sensors.

objtype: (any element type that can be named), optional

Type of the MuJoCo object to which the sensor is attached. This together with the objname attribute determines the actual object. If unspecified, will be mjOBJ_UNKNOWN.

objname: string, optional

Name of the MuJoCo object to which the sensor is attached.

datatype: [real, positive, axis, quaternion], “real”

The type of output generated by this sensor. “axis” means a unit-length 3D vector. “quat” means a unit quaternion. These need to be declared because when MuJoCo adds noise, it must respect the vector normalization. “real” means a generic array (or scalar) of real values to which noise can be added independently.

needstage: [pos, vel, acc], “acc”

The MuJoCo computation stage that must be completed before the user callback mjcb_sensor() is able to evaluate the output of this sensor.

dim: int, required

Number of scalar outputs of this sensor.

keyframe (*)

This is a grouping element for keyframe definitions. It does not have attributes. Keyframes can be used to create a library of states that are of interest to the user, and to initialize the simulation state to one of the states in the library. They are not needed by any MuJoCo computations. The number of keyframes allocated in mjModel is the larger of the nkey attribute of size, and the number of elements defined here. If fewer than nkey elements are defined here, the undefined keyframes have all their data set to 0, except for the qpos attribute which is set to mjModel.qpos0. The user can also set keyframe data in mjModel at runtime; this data will then appear in the saved MJCF model. Note that in simulate.cc the simulation state can be copied into a selected keyframe and vice versa.

keyframe/ key (*)

This element sets the data for one of the keyframes. They are set in the order in which they appear here.

name: string, optional

Name of this keyframe.

time: real, “0”

Simulation time, copied into mjData.time when the simulation state is set to this keyframe.

qpos: real(mjModel.nq), default = mjModel.qpos0

Vector of joint positions, copied into mjData.qpos when the simulation state is set to this keyframe.

qvel: real(mjModel.nq), “0 0 …”

Vector of joint velocities, copied into mjData.qvel when the simulation state is set to this keyframe.

act: real(mjModel.na), “0 0 …”

Vector of actuator activations, copied into mjData.act when the simulation state is set to this keyframe.

ctrl: real(mjModel.nu), “0 0 …”

Vector of controls, copied into mjData.ctrl when the simulation state is set to this keyframe.

mpos: real(3*mjModel.nmocap), default = mjModel.body_pos

Vector of mocap body positions, copied into mjData.mocap_pos when the simulation state is set to this keyframe.

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mquat: real(4*mjModel.nmocap), default = mjModel.body_quat

Vector of mocap body quaternions, copied into mjData.mocap_quat when the simulation state is set to this keyframe.

Made with Sphinx and @pradyunsg's Furo