

MocoExtendProblem: Interface Between OpenSim and MATLAB for Rapidly Developing Direct Collocation Goals in Moco

Aravind Sundararajan¹, Varun Joshi², Brian R. Umberger², and Matthew C. O'Neill¹

¹ Department of Anatomy, Midwestern University, Glendale Arizona, USA ² School of Kinesiology, University of Michigan, Ann Arbor, Michigan, USA ¶ Corresponding author

DOI: [10.xxxxxx/draft](https://doi.org/10.xxxxxx/draft)

Software

- [Review](#)
- [Repository](#)
- [Archive](#)

Editor: [Open Journals](#)

Reviewers:

- [@openjournals](#)

Submitted: 01 January 1970

Published: unpublished

License

Authors of papers retain copyright and release the work under a Creative Commons Attribution 4.0 International License ([CC BY 4.0](#)).

Summary

MocoExtendProblem (MEP) is a framework to rapidly develop novel goals for biomechanical optimal control problems using OpenSim Moco ([Dembia et al., 2020](#)) and MATLAB (The Mathworks, Inc., Natick, MA, USA). MEP features several templates for testing and prototyping novel MocoGoals in lieu of rebuilding OpenSim or generating an .omoco file from C++ to load the problem into MATLAB. Instead, users structure custom goals, build them, and call custom goals from MATLAB scripts.

This repository features:

- A build.m script that compiles goals in the custom_goals directory and procedurally constructs the C++/MATLAB class implementations and compiles the MEX interface.
- Compatibility tested with OpenSim 4.2-4.5.
 - OpenSim versions lower than 4.5 require unique modifications to the build pipeline since booleans for division by duration, distance and mass were migrated to the abstract MocoGoal.
- The ability to include MEP as a submodule, build, and use valid custom goals.
- Three example custom goals in the custom_goals and custom_goals_compat directories.

Statement of need

OpenSim is an open-source software platform for modeling musculoskeletal structures and creating dynamic simulations of movement ([Seth et al., 2018](#)). OpenSim enables researchers and clinicians to investigate how biological and non-biological structures respond to different loads, postures and activities in both static and dynamic situations. OpenSim has been used to study a wide range of biomechanical problems, such as the mechanics of walking and running (e.g. [Falisse et al., 2019](#)), the impact of injury or disease on movement (e.g. [Johnson et al., 2022](#)), and the effectiveness of rehabilitation exercises (e.g. [Spomer et al., 2023](#)).

OpenSim Moco ([Dembia et al., 2020](#)) employs an optimization paradigm called direct collocation to solve trajectory optimization problems that range from solving for muscle forces, to tracking experimental data, and fully predictive simulations. Direct collocation is a numerical optimal control method ([Kelly, 2017](#)) that is computationally efficient and is used extensively in computational approaches to understanding biological movement. While direct collocation is powerful, Moco only provides a fixed set of optimization goals. It can be daunting for many users to develop custom goals in C++. We developed MEP so Moco users without experience compiling C++ can still write and test custom goals. The OpenSim interfaces are created

40 with SWIG, as opposed to MEX, which can be daunting for even experienced biomechanists.
41 MocoExtendProblem was developed using MATLAB versions 2022a. Running build.m will
42 compile MocoGoals in the custom_goals directory, or in the custom_goals_compat directory
43 for OpenSim versions pre-4.5.

44 Typically, OpenSim interfaces are generated with SWIG, as opposed to MEX, which can be
45 challenging for even experienced biomechanists. MEP was developed using MATLAB (v.
46 2022a), which is a multimodal software platform that is commonly used by biomechanics
47 researchers. MEP only requires that CMake and msbuild from Visual Studio 2019 or higher be
48 added to the system PATH environment variable to use MATLAB's MEX compiler with C++.

49 With MEP, users can run build.m to compile MocoGoals in the custom_goals directory, or
50 in the custom_goals_compat directory for OpenSim versions pre-4.5. build.m will procedu-
51 rally construct both extend_problem.m and ExtendProblem.cpp by parsing the header files
52 of the discovered goals within the custom_goals directory. Both ExtendProblem.cpp and
53 extend_problem.m generate bindings to instantiate custom goals placed in the custom_goals
54 directory. Custom goals can be compiled with Visual Studio 2019 or higher and then MATLAB's
55 MEX compiler is used to compile the ExtendProblem class. ExtendProblem.cpp leverages the
56 C++ library mexplus (Yamaguchi, 2018) to gain access to MEX entry points through C++
57 macros.

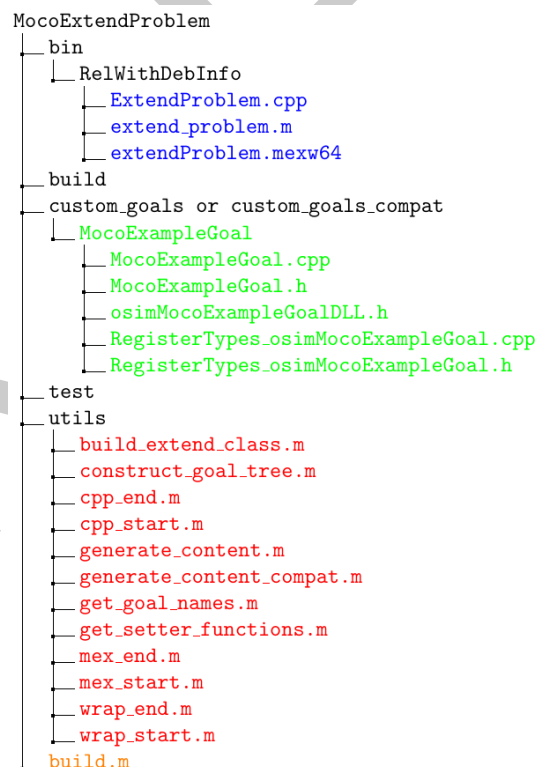


Figure 1: MEP framework. The researcher runs the build.m script (orange) that subsequently calls methods in the utils folder (red) which are tasked with reading the custom_goals folder (green) and procedurally construct the mex and the interface class that calls the mex (blue). Each custom goal (green) is handled as its own compiled plugin.

58 To create a new goal with MEP:

- 59 1. OpenSim 4.5+ users should copy a goal in the custom_goals directory while 4.2-4.4
- 60 users should copy a goal in custom_goals_compat.
- 61 2. Replace mentions of the original goal name to that of your new custom goal name in

each of the 5 files and file names, being careful to also modify the include guards in the dll and register types header files.

3. Reimplement `constructProperties()`, `initializeOnModelImpl()`, `calcIntegrandImpl()`, `calcGoalImpl()` such that they describe your custom goal.

To incorporate `extend_problem` goals into an existing MATLAB script, a C-style pointer to the instantiated `MocoProblem` is passed as a constructor argument to the `extend_problem.m` class that wraps the MEP MEX. Class methods of `extend_problem.m` (Figure 1; blue) are then used to add custom goals to the `MocoProblem`.

```
cptr = uint64(problem.getCPtr(problem));
ep = extend_problem(cptr);
ep.addMocoCustomGoal('custom_goal',weight,power,divide_by_distance);
```

This paradigm has implications for OpenSim and MATLAB developers beyond the scope of just incorporating novel `MocoGoals`; these same tools can be used to extend other classes and easily incorporate them into existing MATLAB-OpenSim scripts. We have posted all tools, instructions and simulation results related to this project on [GitHub](#) and [SimTK.org](#).

Requirements

- Download and install OpenSim from [SimTK](#) and follow the documentation for setting up OpenSim's MATLAB scripting environment.
- Follow the instructions (OpenSim) to download necessary dependencies for both scripting in MATLAB and C++ development.
- In MATLAB, configure MEX with `mex -setup C++` to use the MS VisualStudio 2019+.

Showcases

To demonstrate the utility of this framework, we generated a two-dimensional (2-D) walking simulation using the MATLAB-OpenSim API (Denton & Umberger, 2023). The base code uses the built-in `MocoControlEffortGoal` and `MocoAverageSpeedGoal` to generate tracking and predictive simulations of minimum effort walking at an average speed of 1.3 m s⁻¹. Additionally, each objective function includes implicit acceleration and auxiliary derivative terms that are minimized to ensure smooth trajectories.

Since Moco lacks built-in gait stability goals, we developed three stability goals using MEP `build.m` to create an `ExtendProblem` class that adds these to an existing `MocoProblem` (Figure 1; blue). The first is a base of support (Equation 1 BOS) criterion in which the whole-body center of mass (COM) is optimized to lay between the two hindfeet COMs projected to the ground reference frame, the second is a zero-moment-point goal (Equation 2 ZMP) where the center of mass tracks the computed zero-tilting moment location, and the third is a marker acceleration minimization goal (Equation 3 ACC_{marker}) that minimizes the explicit accelerations of a marker placed on the head (marker location is arbitrary and can be set by the user).

MEP's `build.m` was used to generate an `ExtendProblem` class that adds these new stability cost terms:

$$J_{BOS} = W_1 EFF^2 + W_2 ACC_{smoothing} + W_3 BOS \quad (1)$$

$$J_{zmp} = W_1 EFF^2 + W_2 ACC_{smoothing} + W_3 ZMP \quad (2)$$

$$J_{acc} = W_1 EFF^2 + W_2 ACC_{smoothing} + W_3 ACC_{marker} \quad (3)$$

98 The results of each multi-objective predictive simulation, in which the stability criterion was
99 compiled using MEP, is shown against the results from a tracking simulation (Figure 2; Table 1)
100 that closely-matched experimental data (Denton & Umberger, 2023). As the purpose was
101 to demonstrate the utility of MEP, we did not tune the stability term weights to match the
102 tracking result as closely as possible.

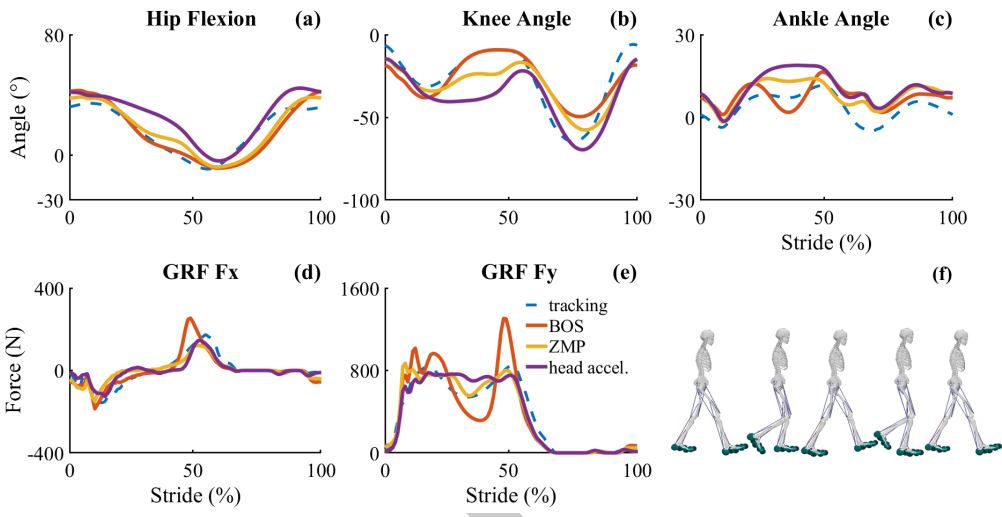


Figure 2: Sagittal plane hip, knee and ankle angles (a-c), vertical and A-P ground reaction forces (d-e), the 11 degree-of-freedom, 18 muscle sagittal plane human walking model used for tracking and predictive simulations (f)

Table 1: Objective cost and term breakdown for three predictive simulations using MEP.

	Objective cost	Effort cost	Smoothing cost	Stability cost
J_{BOS}	3.759046	2.270912	0.683608	0.794155
J_{ZMP}	4.184254	2.751212	0.725837	0.686290
J_{accel}	4.774932	3.797785	0.793123	0.174308

103 While these examples used planar gait simulations, MEP is agnostic to model complexity or task,
104 and is being used successfully in our ongoing research (e.g. Joshi et al., 2022; Sundararajan
105 et al., 2023) of locomotor performance in humans and other animals. GNU Octave support
106 would require minimal syntactical modification. An additional benefit of sequestering novel
107 goals into ExtendProblem is being able to back-port goals from a newer OpenSim version
108 to an older version (i.e. taking a goal from OpenSim 4.4 and bringing that functionality to
109 4.2). Ultimately, MEP offers a modular framework to rapidly develop, test and compare novel
110 MocoGoals for features beyond OpenSim Moco's current scope.

111 **Funding**

112 This work was supported by the National Science Foundation (BCS 2018436 and BCS 2018523).

113 **References**

114 Dembia, C. L., Bianco, N. A., Falisse, A., Hicks, J. L., & Delp, S. L. (2020). OpenSim
115 moco: Musculoskeletal optimal control. *PLOS Computational Biology*, 16(12), 1–21.
116 <https://doi.org/10.1371/journal.pcbi.1008493>

- 117 Denton, A. N., & Umberger, B. R. (2023). Computational performance of musculoskeletal
118 simulation in OpenSim moco using parallel computing. *International Journal for Numerical*
119 *Methods in Biomedical Engineering*, 39(12), e3777. <https://doi.org/10.1002/cnm.3777>
- 120 Falisse, A., Serrancolí, G., Dembia, C. L., Gillis, J., Jonkers, I., & De Groote, F. (2019). Rapid
121 predictive simulations with complex musculoskeletal models suggest that diverse healthy
122 and pathological human gaits can emerge from similar control strategies. *Journal of The*
123 *Royal Society Interface*, 16(157), 20190402. <https://doi.org/10.1098/rsif.2019.0402>
- 124 Johnson, R. T., Bianco, N. A., & Finley, J. M. (2022). Patterns of asymmetry and energy cost
125 generated from predictive simulations of hemiparetic gait. *PLOS Computational Biology*,
126 18(9), 1–26. <https://doi.org/10.1371/journal.pcbi.1010466>
- 127 Joshi, V., Boyer, K., & Umberger, B. R. (2022). Optimal control gait simulations of older adults
128 predict foot placement trends not captured by reflex-based models. In *the Proceedings of*
129 *the North American Congress on Biomechanics*. North American Congress on Biomechanics.
- 130 Kelly, M. (2017). An introduction to trajectory optimization: How to do your own direct
131 collocation. *SIAM Review*, 59(4), 849–904. <https://doi.org/10.1137/16M1062569>
- 132 Seth, A., Hicks, J. L., Uchida, T. K., Habib, A., Dembia, C. L., Dunne, J. J., Ong, C. F.,
133 DeMers, M. S., Rajagopal, A., Millard, M., Hamner, S. R., Arnold, E. M., Yong, J. R.,
134 Lakshmikanth, S. K., Sherman, M. A., Ku, J. P., & Delp, S. L. (2018). OpenSim: Simulating
135 musculoskeletal dynamics and neuromuscular control to study human and animal movement.
136 *PLOS Computational Biology*, 14(7), 1–20. <https://doi.org/10.1371/journal.pcbi.1006223>
- 137 Spomer, A., Conner, B., Schwartz, M., Lerner, Z., & Steele, K. (2023). Audiovisual biofeedback
138 amplifies plantarflexor adaptation during walking among children with cerebral palsy. *Journal*
139 *of NeuroEngineering and Rehabilitation*, 20. <https://doi.org/10.1186/s12984-023-01279-5>
- 140 Sundararajan, A., Larson, S. G., Umberger, B. R., & O'Neill, M. C. (2023). Optimal control
141 simulations of 3-d walking in humans and bipedal chimpanzee. In *the Proceedings of The*
142 *American Society of Biomechanics*. American Society of Biomechanics.
- 143 Yamaguchi, K. (2018). Mexplus. In *GitHub repository*. GitHub. [https://github.com/kyamagu/](https://github.com/kyamagu/mexplus)
144 [mexplus](https://github.com/kyamagu/mexplus)