Information Specific to Generating Simulations

The following tables contain parameters used to generate the simulations. Additional parameters may be found in the setup files used for running scaling, inverse kinematics, residual reduction, computed muscle control, inverse dynamics, and perturbation.

Subjects' age, gender, body mass, leg length, and walking speeds are provided (Tables 1 and 2). One step of the simulation process was to calculate small adjustments to the torso mass and the torso center of mass location that would minimize the residual forces and residual torques required to ensure dynamic consistency between the measured ground reaction forces and computed kinematics. For each subject, these recommended adjustments were calculated for the simulations at each of the four speeds, and the mean values were applied to each subject-specific model (Table 3).

The timing of gait cycle events for both limbs is also reported (Table 4). Each simulation began during the single-limb stance phase of one limb and ended at terminal swing of that limb; hence that limb was labeled the "swing limb" and the other limb was labeled the "stance limb." The simulation times were shifted such that t=0 at initial contact of the swing limb on a force plate. The initial contact time of the stance limb was also based on force plate data. To compute the duration of a gait cycle, the subsequent times of initial contact events for each limb ("next initial contact" in Table 4) were estimated from marker and kinematic data, as subjects typically did not execute subsequent clean force plate strikes. Swing limb toe-off was identified from force plate data. The foot-flat and heel-off times were required to appropriately engage the foot-floor springs during the perturbation analysis, and they were estimated from visual inspection of the simulations and from analyzing the kinematics of the model's foot segment with respect to the floor.

The software used to generate the simulations in this dissertation was a pre-release developer version of OpenSim that is not available for public use. However, the simulations have been regenerated using OpenSim 1.5.5, which is an official software release available to the public. During the regeneration process, a small error in the orientation of the model's left ankle axis was corrected; this error was found not to significantly affect the results reported in Liu et al. (in press, 2008).

Table 1: Subject characteristics and simulation ID labels

simulation ID	gender	age *years*	mass *kg*	leg length *m*
GIL01	F	10.2	41.1	0.77
GIL02	F	14.6	66.0	0.90
GIL03	M	13.8	41.6	0.84
GIL04	F	11.3	32.4	0.72
GIL06	F	14.1	81.9	0.81
GIL08	F	14.5	61.9	0.94
GIL11	F	18.0	63.1	0.84
GIL12	M	7.0	26.1	0.66

Table 2: Subject walking speeds

simulation ID	very slow speed *m/s (nondim.)**	slow speed *m/s (nondim.)**	free speed *m/s (nondim.)**	fast speed *m/s (nondim.)**
GIL01	0.57 (0.21)	0.67 (0.24)	1.01 (0.37)	1.40 (0.51)
GIL02	0.49 (0.16)	0.80 (0.27)	1.21 (0.41)	1.52 (0.51)
GIL03	0.55 (0.19)	0.70 (0.24)	1.29 (0.45)	2.00 (0.70)
GIL04	0.49 (0.19)	0.94 (0.35)	1.15 (0.44)	1.34 (0.50)
GIL06	0.50 (0.18)	0.81 (0.29)	1.11 (0.39)	1.42 (0.50)
GIL08	0.56 (0.19)	0.70 (0.23)	1.12 (0.37)	1.62 (0.53)
GIL11	0.61 (0.21)	0.80 (0.28)	1.17 (0.41)	1.64 (0.57)
GIL12	0.56 (0.22)	0.61 (0.24)	1.15 (0.45)	1.51 (0.60)

* Speeds are reported in m/s and nondimensional units (actual speed normalized by $\sqrt{gL_{leg}}$

Table 3: Changes to torso mass and center of mass location computed by OpenSim to improve dynamic consistency

sim. ID	body mass (kg)	trial	change in torso mass (kg)	change in torso COM location (cm)	
				fore-aft	mediolateral
GIL01	41.1	very slow	0.35	0.34	0.12
		slow	0.50	-3.68	-0.87
		free	0.54	-0.42	-0.99
		fast	0.41	-0.33	0.88
		mean	**0.45**	**-1.02**	**-0.21**
GIL02	66.0	very slow	0.54	0.12	-0.08
		slow	0.77	-0.72	-0.39
		free	0.57	0.32	-0.11
		fast	0.62	-0.11	-0.34
		mean	**0.62**	**-0.10**	**-0.23**
GIL03	41.6	very slow	0.20	0.26	-0.50
		slow	0.21	0.10	-0.06
		free	0.08	0.21	-0.46
		fast	-0.51	1.12	0.39
		mean	**-0.01**	**0.42**	**-0.16**
GIL04	32.4	very slow	0.12	-0.62	0.49
		slow	0.13	-0.09	-0.48
		free	0.03	0.79	-0.36
		fast	-0.08	1.11	0.45
		mean	**0.05**	**0.30**	**0.02**
GIL06	81.9	very slow	0.83	-1.94	-0.18
		slow	0.56	-1.46	0.46
		free	0.56	-2.44	-0.61
		fast	0.77	-2.56	-0.49
		mean	**0.68**	**-2.10**	**-0.21**
GIL08	61.9	very slow	-0.69	-1.38	-0.52
		slow	-0.82	-1.06	-0.01
		free	-1.08	0.23	-0.44
		fast	-0.89	0.59	-0.23
		mean	**-0.87**	**-0.40**	**-0.30**
GIL11	63.1	very slow	0.44	0.10	-0.62
		slow	-0.64	0.35	-0.58
		free	-0.19	0.26	-0.32
		fast	-0.54	0.57	0.08
		mean	**-0.23**	**0.32**	**-0.36**
GIL12	26.1	very slow	0.17	2.85	-1.36
		slow	0.31	0.29	0.92
		free	-0.04	0.64	-0.73
		fast	0.17	0.43	0.49
		mean	**0.15**	**1.05**	**-0.17**

Table 4: Gait cycle event times

			stance limb events (s)				swing limb events (s)		
sim. ID	trial	stance limb	*initial contact*	*foot-flat*	*heel-off*	*next initial contact*	*heel-off*	*toe-off*	*next initial contact*
GIL01	very slow	R	0.83	0.94	1.56	2.52	0.83	1.06	1.66
	slow	R	0.84	0.96	1.52	2.42	0.84	1.07	1.73
	free	R	0.59	0.68	1.08	1.73	0.48	0.74	1.18
	fast	L	0.49	0.56	0.84	1.42	0.36	0.59	0.97
GIL02	very slow	R	0.98	1.08	3.00	2.94	0.98	1.36	1.96
	slow	L	0.66	0.73	1.29	2.06	0.63	0.88	1.35
	free	L	0.56	0.64	0.98	1.65	0.48	0.68	1.09
	fast	L	0.47	0.53	0.73	1.45	0.32	0.57	0.97
GIL03	very slow	R	0.77	0.92	1.37	2.39	0.65	1.01	1.60
	slow	L	0.76	0.88	1.40	2.23	0.73	0.96	1.52
	free	L	0.51	0.60	0.93	1.51	0.44	0.62	1.03
	fast	R	0.36	0.41	0.56	1.06	0.21	0.40	0.73
GIL04	very slow	L	0.94	1.24	1.74	2.93	0.84	1.28	1.95
	slow	L	0.60	0.71	1.11	1.83	0.45	0.74	1.25
	free	R	0.57	0.66	1.00	1.69	0.42	0.67	1.11
	fast	L	0.51	0.60	0.95	1.59	0.43	0.61	1.06
GIL06	very slow	R	0.97	1.14	1.84	3.06	0.96	1.33	1.97
	slow	R	0.66	0.74	1.24	1.99	0.56	0.84	1.35
	free	R	0.54	0.63	1.00	1.67	0.48	0.67	1.15
	fast	R	0.51	0.59	0.92	1.55	0.38	0.60	1.05
GIL08	very slow	R	0.85	0.96	1.61	2.58	0.80	1.11	1.76
	slow	R	0.76	0.87	1.44	2.23	0.71	0.98	1.50
	free	R	0.59	0.68	1.10	1.76	0.52	0.72	1.19
	fast	R	0.48	0.56	0.77	1.43	0.38	0.59	0.98
GIL11	very slow	R	0.78	0.92	1.61	2.56	0.77	1.11	1.66
	slow	R	0.78	0.88	1.36	2.21	0.68	0.96	1.55
	free	R	0.54	0.61	0.96	1.59	0.46	0.66	1.09
	fast	L	0.45	0.52	0.74	1.34	0.32	0.54	0.89
GIL12	very slow	R	0.91	0.97	1.58	2.77	0.80	1.19	1.86
	slow	L	0.82	0.94	1.52	2.34	0.81	1.03	1.66
	free	R	0.45	0.53	0.84	1.41	0.39	0.55	1.00
	fast	L	0.41	0.48	0.66	1.29	0.35	0.48	0.87

Comments on testing and analyzing these simulations

We need simulations to answer questions about human movement because experimental protocols, such as measuring muscle forces in children during walking, are impractical. To have confidence in the results of simulation studies, however, thorough testing of the simulations is necessary. The testing requirements can be divided into three main areas: testing the musculoskeletal model, testing the methods by which the muscle excitations are generated that drive the model to follow subject-specific walking dynamics, and testing the methods used to analyze the simulations. We focused on testing aspects of the simulations that are most relevant to answering questions about support and progression during walking. The musculoskeletal geometry and actuator force-generating properties of the model in this study have been tested previously (Delp et al., 1990; Thelen and Anderson, 2006) to ensure that they adequately represent normal human anatomy and physiology. The methods we used to generate muscle excitations that drive the model have also been previously tested (Thelen and Anderson, 2006; Delp et al., 2007). Additionally, we tested each simulation in this study by comparing the simulated kinematics, sagittal joint moments, and muscle excitations to experimental values measured for that walking trial (e.g., Liu et al. (in press, 2008) Figs. 2 - 4). The simulation reproduced joint kinematics with high fidelity. The joint moments computed from summing actuator forces matched the joint moments computed from inverse dynamics very well. In cases where the computed excitation patterns were substantially different from experimental data from our subjects or data from the literature (Perry, 1992; Hof et al., 2002; den Otter et al., 2004; Cappellini et al., 2006; Schwartz et al., 2008), the excitations were constrained to follow more appropriate patterns. However, EMG data were not available for all lower extremity muscles for a range of walking speeds, making it impossible to compare simulated and experimental muscle activity for all muscles in the model. We were able to produce simulated excitation patterns that generally match experimentally-recorded EMG data for major muscle groups, although the timing of peak activity was slightly delayed for some muscles (e.g., Liu et al. (in press, 2008) Fig. 4. gastrocnemius and soleus activity). We could have forced the simulated excitations to follow experimental EMG data more closely. However, the compensations required by computed muscle control algorithm to accommodate large imposed changes in muscle excitations often cause substantial deviations in excitation patterns of other muscles and may also lead to poorly-tracked kinematics. We believe that the results of testing the simulations' kinematics, sagittal joint moments, and muscle excitations are adequate for investigating the questions posed in this study. Investigators who use these simulations to addresses other scientific questions need to perform additional testing to determine if the simulations are sufficiently accurate for their studies.

We also tested the perturbation analysis (Liu et al., 2006) used in this study. This analysis quantifies the contributions of any model actuator, or gravity, to a particular acceleration. In the studies described in Liu et al. (2006) and this chapter, we examined actuator contributions to vertical and fore-aft linear accelerations of the body mass center during normal walking, but this analysis can also be applied to examine other accelerations of interest, such as the angular acceleration of the knee (Goldberg et al., 2004; Arnold et al., 2007). To test our application of the perturbation analysis, we compared the summed contributions from all actuators and gravity to the fore-aft and vertical accelerations of the body mass center (e.g., Liu et al. (2006), Fig. 1) and examined how well the superposition of the contributions from actuators and gravity matched the mass center accelerations. We observed reasonable superposition for each simulation, lending confidence to our interpretation of muscle contributions to support and progression during walking.

We did notice that results from the perturbation analysis were sensitive to foot-floor contact patterns. For the simulations in Liu et al. (in press, 2008), we represented foot-floor contact by applying linear and torsional spring-damper units to the model's feet during the stance phase. The spring-damper units resisted motions of the foot that deviated from the center of pressure trajectory, simulating the change in ground reaction forces due to perturbations in muscle force. Implementation of these foot springs posed several challenges, including selecting appropriate stiffness and damping constants, identifying the foot-floor contact events at which to turn on or turn off the springs, and choosing the exponential time constants governing the rates at which the springs were engaged and disengaged. The spring-damper units were made very stiff to model barefoot contact with a hard floor and to ensure a fast force response to perturbed dynamics. However, sufficient damping was required to limit the resulting force oscillations. Foot contact events determined the on-off times for the spring-damper units: the linear units were turned on at initial contact and turned off at toe-off, and the torsional units were turned on at foot-flat and turned off at heel-off. Initial contact and toe-off were identified from vertical ground reaction force data. The foot-flat and heel-off times were estimated from visual inspection of the simulations and from analyzing the kinematics of the model's foot segment with respect to the floor. We selected exponential time constants that resulted in very fast, but smooth, behavior of the springs as they turned on and off at the appropriate times.

Another important aspect of the perturbation analysis is the duration of the perturbation, for which we used 0.03 s. As described in Liu et al. (2006), this duration was selected to allow sufficient time for the foot spring-damper units to respond to a perturbed muscle force, but to prevent kinematics from deviating significantly. During the simulations of fast walking, however, the kinematics changed very quickly during perturbations, resulting in less accurate superposition when comparing the estimated contributions from actuators and gravity to the nominal mass center accelerations. Reducing the perturbation duration to 0.025 s did not significantly improve superposition results, and we hesitated to further reduce the duration because the foot spring-damper units need sufficient response time.

If these simulations were to be used to address a different scientific question (e.g., analysis of body segmental powers or of mediolateral body accelerations), then different testing protocols of the simulations may be appropriate, and could accordingly require modifications to the musculoskeletal model, the methods used to compute muscle excitations, and/or the perturbation analysis. We encourage users of these simulations to modify and improve the simulations and analyses as needed, and to share their changes with others at http://simtk.org.

References

Arnold, A.S., Schwartz, M.H., Thelen, D.G. and Delp, S.L., 2007. Contributions of muscles to terminal-swing knee motions vary with walking speed. J Biomech 40, 3660-71.

Cappellini, G., Ivanenko, Y.P., Poppele, R.E. and Lacquaniti, F., 2006. Motor patterns in human walking and running. J Neurophysiol 95, 3426-37.

Delp, S.L., Anderson, F.C., Arnold, A.S., Loan, P., Habib, A., John, C.T., Guendelman, E. and Thelen, D.G., 2007. OpenSim: open-source software to create and analyze dynamic simulations of movement. IEEE Trans Biomed Eng 54, 1940-50.

Delp, S.L., Loan, J.P., Hoy, M.G., Zajac, F.E., Topp, E.L. and Rosen, J.M., 1990. An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures. IEEE Transactions on Biomedical Engineering 37, 757-767.

den Otter, A.R., Geurts, A.C., Mulder, T. and Duysens, J., 2004. Speed related changes in muscle activity from normal to very slow walking speeds. Gait Posture 19, 270-8.

Goldberg, S.R., Anderson, F.C., Pandy, M.G. and Delp, S.L., 2004. Muscles that influence knee flexion velocity in double support: implications for stiff-knee gait. J Biomech 37, 1189-96.

Hof, A.L., Elzinga, H., Grimmius, W. and Halbertsma, J.P., 2002. Speed dependence of averaged EMG profiles in walking. Gait Posture 16, 78-86.

Liu, M.Q., Anderson, F.C., Pandy, M.G. and Delp, S.L., 2006. Muscles that support the body also modulate forward progression during walking. J Biomech 39, 2623-30.

Liu, M.Q., Anderson, F.C., Schwartz, M.H. and Delp, S.L., in press, 2008. Muscle contributions to support and progression over a range of walking speeds. Journal of Biomechanics.

Perry, J., 1992. Gait analysis: normal and pathological function. SLACK Inc., Thorofare, NJ.

Schwartz, M.H., Rozumalski, A. and Trost, J.P., 2008. The effect of walking speed on the gait of typically developing children. J Biomech 41, 1639-50.

Thelen, D.G. and Anderson, F.C., 2006. Using computed muscle control to generate forward dynamic simulations of human walking from experimental data. J Biomech 39, 1107-15.

Brief description of files contained in a subject download

The table below lists the files that are within a zipped subject download. The “setup” files used for running scaling, inverse kinematics, residual reduction, computed muscle control, inverse dynamics, and perturbation contain relative paths that assume a directory hierarchy as shown in the table. If you change the directory hierarchy, be sure to change the setup file paths accordingly. Subject GIL01 is used as an example below, but the files are similar for all subjects. Perturbation results are currently available only for GIL01, but the results for the remaining subjects will be posted in the near future.

Directory	***Contents** (directories in **bold**)*	***Usage***	***Notes***
GIL01.zip			
	GIL01		
	gait2392_simbody.osim	input	Unscaled musculoskeletal model
	gait2392_GIL_Scale_Tasks.xmls	input	Task file used to scale all subject-specific models
	gait2392_GIL_Scale_MeasurementSet.xml	input	Measurement file used to scale all subject-specific models
	gait2392_GIL_Scale_MarkerSet.xml	input	Marker set file used to scale all subject-specific models
	gait2392_GIL_IK_Tasks.xml	input	Task file used in inverse kinematics for all simulations
/GIL01			GIL01 is used here as a representative subject. Other subject directories will have similar contents.
	StaticTrial		
	XSlow2		
	Slow3		
	Free4		
	Fast5		

Directory	***Contents*** *(directories in* ***bold****)*	***Usage***	***Notes***
/GIL01 (continued)	GIL01_RRA_Actuators.xml	input	Actuator file used during RRA for all trials for this subject
	GIL01_RRA_ControlConstraints.xml	input	Control constraints file used during RRA for all trials for this subject
	GIL01_RRA_Tasks.xml	input	Task file used during RRA for all trials for this subject
	GIL01_CMC_Actuators.xml	input	Actuator file used during CMC for all trials for this subject
	GIL01_CMC_Tasks.xmls	input	Task file used during CMC for all trials for this subject
	GIL01_gait2392_simbody.osim	*output*	Scaled model for this subject (generated by running the "scale" step)
	GIL01_gait2392_simbody_adjusted.osim	*output (manual)*	Scaled model after adjustments to torso mass and center of mass (adjustments were made manually; see M. Liu's dissertation, Appendix D)
/GIL01/StaticTrial			
	GIL01_Setup_Scale.xml	input	Setup file to run scaling on this subject
	GIL01_static.mot	input	Input generalized coordinates file for this subject's static trial
	GIL01_static.trc	input	Input marker trajectory file for this subject's static trial
	GIL01_gait2392_simbody_static_output.mot	*output*	Output generalized coordinates file generated by scaling
	GIL01_gait2392_simbody_ScaleSet_Applied.xml	*output*	Generic output file generated by scaling, which is unnecessary for subsequent steps
	markers_coords_ik.sto	*output*	Output marker file generaged by scaling
	out.log	*output*	Output log file generated by scaling
	err.log	*output*	Output error file generated by scaling
	GIL01.mp	subject data	Subject data file generated by Vicon software at gait laboratory, contains subject anthropometric measurements

Directory	***Contents*** *(directories in* ***bold****)*	***Usage***	***Notes***
/GIL01/Free4			Free4 is used as a here as a representative walking trial. Other walking trial directories will have similar contents.
	IK		
	RRA		
	CMC		
	INVDYN		
	Perturb		
	GIL01_free4EmgEng.mot	subject data	EMG data from surface electrodes for this walking trial (contains for each muscle: rectified data for this stride, linear envelope for this stride, average envelope for multiple strides, average envelope plus 1 standard deviation, average envelope minus 1 standard deviation)
	GIL01_free4Moments.mot	subject data	Sagittal hip, knee, and ankle moments, computed in gait lab using inverse dynamics (Nmm/kg)
/GIL01/Free4/IK			
	GIL01_free4_Setup_IK.xml	input	Setup file to run inverse kinematics for this trial
	GIL01_free4.mot	input	Input generalized coordinates file for this trial
	GIL01_free4.trc	input	Input marker trajectory file for this trial
	GIL01_free4_ik.mot	*output*	Output generalized coordinates file for this trial
	markers_coords_ik.sto	*output*	Output marker file generated by inverse kinematics
	out.log	*output*	Output log file generated by inverse kinematics
	err.lot	*output*	Output error file generated by inverse kinematics

Directory	***Contents** (directories in **bold**)*	***Usage***	***Notes***
/GIL01/Free4/RRA			
	Results		See OpenSim User's Guide for description of residual reduction output files
	GIL01_free4_Setup_RRA.xml	input	Setup file to run residual reduction for this trial
	desiredKinematics_padded.sto	*output*	Output file that contains kinematics (from inverse kinematics step) after the data have been augmented to improve spline fits at start and end of data
	desiredKinematics_splinefit_accelerations.sto	*output*	Output file that contains the accelerations computed by spline-fitting and twice differentiating the padded kinematics
	out.log	*output*	Output log file generated by residual reduction
	err.log	*output*	Output error file generated by residual reduction
/GIL01/Free4/CMC			
	Results		See OpenSim User's Guide for description of computed muscle control output files
	GIL01_free4_Setup_CMC_Unconstrained.xml	input	Setup file to run computed muscle control without imposed muscle excitation constraints for this trial
	GIL01_free4_Setup_CMC_Constrained.xml	input	Setup file to run computed muscle control with imposed muscle excitation constraints for this trial
	GIL01_free4_CMC_ControlConstraints_Unconstrained.xml	input	Control constraints file, without imposed muscle excitation constraints for this trial
	GIL01_free4_CMC_ControlConstraints_Constrained.xml	input	Control constraints file, with imposed muscle excitation constraints for this trial
	desiredKinematics_padded.sto	*output*	Output file that contains kinematics (from inverse kinematics step) after the data have been augmented to improve spline fits at start and end of data
	desiredKinematics_splinefit_accelerations.sto	*output*	Output file that contains the accelerations computed by spline-fitting and twice differentiating the padded kinematics
	out.log	*output*	Output log file generated by computed muscle control
	err.log	*output*	Output error file generated by computed muscle control

Directory	***Contents*** *(directories in* ***bold****)*	***Usage***	***Notes***
/GIL01/Free4/INVDYN			
	Results		See OpenSim User's Guide for description of inverse dynamics output files
	GIL01_free4_Setup_invdyn_ik.xml	input	Setup file to run inverse dynamics on output from inverse kinematics for this trial
	GIL01_free4_Setup_invdyn_rra.xml	input	Setup file to run inverse dynamics on output from residual reduction for this trial
	GIL01_free4_Setup_invdyn_cmc.xml	input	Setup file to run inverse dynamics on output from computed muscle control for this trial
	check.xml	*output*	Output file that should be identical to input setup file (no longer used except by developers)
	out.log	*output*	Output log file generated by inverse dynamics
	err.log	*output*	Output error file generated by inverse dynamics
/GIL01/Free4/Perturb			
	Results		See OpenSim User's Guide for description of perturbation output files. (Perturbation results are currently posted only for subject GIL01)
	GIL01_free4_Setup_Peturb.xml	input	Setup file to run perturbation analysis for this trial