

Supplementary material describing Arm26

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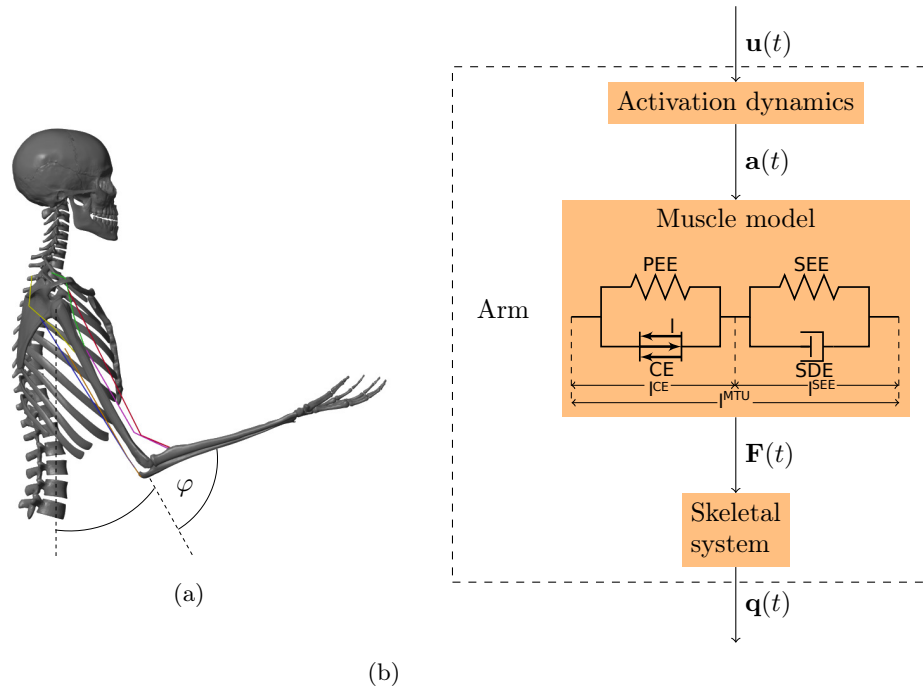


Figure S1: (a) Visualization of the musculoskeletal model of the arm and the definition of the shoulder angle $\theta(t)$ and the elbow angle $\varphi(t)$ and (b) Structure of the arm model: the motor command $u(t)$ is fed into the model of the activation dynamics of muscles which relates the neuronal stimulation to muscular activity $a(t)$ that drives the muscle model. The muscles produce forces $F(t)$ that act on the skeletal system resulting in a simulated movement $q(t) = [\varphi(t), \psi(t)]$ of the arm.

The neuro-musculoskeletal model *Arm26* consists of a musculoskeletal model of the arm with two degrees of freedom actuated by six muscles and a controller. The model is implemented using Matlab[®] R2018a/Simulink[®] with the Simscape Multibody[™] environment. For a better overview, the implementation of the model is divided into three parts: the mechanical part (representing the bone structure and the muscle routing), the actuation of this mechanical part (muscle-tendon structures) and the controller (nervous system) which provides the input to the actuation part.

1 Musculoskeletal model of the arm: Mechanics and Actuation

The musculoskeletal model *Arm26* of the human arm uses the same geometry and muscle parameters as the simulation model described in [Driess et al. \(2018\)](#) which is based on [Bayer et al. \(2017\)](#). It consists of two rigid bodies (lower and upper arm) that are connected via two one-degree-of-freedom revolute joints that represent the shoulder and elbow joint. This multibody system is actuated by six muscle-tendon units (MTU), four monoarticular and two biarticular muscles (see [Figure S1a](#)). The muscles are modeled as lumped muscles, i.e. they represent a multitude of anatomical muscles:

1. Monoarticular Elbow Flexor (MEF) (short: Elbow Flexor (EF)):
m. brachioradialis, m. brachialis, m. pronator teres, m. extensor carpi radialis
2. Monoarticular Elbow Extensor (MEE) (short: Elbow Extensor (EE)):
m. triceps lateralis, m. triceps medialis, m. anconeus, m. extensor carpi ulnaris
3. Biarticular Elbow Flexor Shoulder Anteversion (BEFSA) (short: Biarticular Flexor (BF)):
m. biceps brachii caput longum and caput breve
4. Biarticular Elbow Extensor Shoulder Retroversion (BEESR) (short: Biarticular Extensor (BE)):
m. triceps brachii caput longum
5. Monoarticular Shoulder Anteversion (MSA) (short: Shoulder Flexor (SF)):
m. deltoideus (pars clavicularis, anterior, lateral), m. superior pectoralis major, m. coracobrachialis
6. Monoarticular Shoulder Retroversion (MSR) (short: Shoulder Extensor (SE)):
m. deltoideus (pars spinalis, posterior), m. latissimus dorsi

The MTU structure is modeled using an extended Hill-type muscle model as described in [Haeufle et al. \(2014\)](#) with muscle activation dynamics as introduced by [Hatze \(1977\)](#). The muscle model is a macroscopic model consisting of four elements: the contractile element (CE), the parallel elastic element (PEE) and the serial elastic element (SEE) and serial damping element (SDE), as illustrated in [Figure S1b](#). The inputs to the muscle model are the length of the MTU l^{MTU} , the contraction velocity of the MTU \dot{l}^{MTU} and the muscular activity a . The output of the muscle model is a one-dimensional muscle force F^{MTU} . This force drives the movement of the skeletal system. For the routing of the muscle path around the joints, deflection ellipses are implemented as described by [Hammer et al. \(2019\)](#) (see [Figure S2](#)). The muscle path can move within these ellipses and is deflected as soon as it touches the boundary.

All in all, the governing model dependencies for all muscles $i = 1, \dots, n$ are:

$$\dot{l}_i^{\text{CE}} = f_{\text{CE}}(l_i^{\text{CE}}, l_i^{\text{MTU}}, \dot{l}_i^{\text{MTU}}, a_i) \quad (1)$$

$$\dot{a}_i = f_a(a_i, u_i, l_i^{\text{CE}}) \quad (2)$$

$$F_i^{\text{MTU}} = f_F(l_i^{\text{MTU}}, \dot{l}_i^{\text{MTU}}, l_i^{\text{CE}}, a_i) \quad (3)$$

$$\ddot{\mathbf{q}} = f_q(\dot{\mathbf{q}}, \mathbf{q}, \mathbf{F}^{\text{MTU}}), \quad (4)$$

where \mathbf{q} denotes a generalized state vector, in this case it can be defined as $\mathbf{q} = [\varphi, \psi]$ and $\mathbf{F}^{\text{MTU}} = \{F_i^{\text{MTU}}\}_{i=1}^n$.

The mechanical parameters of the arm segments are taken from [Kistemaker et al. \(2006\)](#) and can be found in [Table S1](#). The positions and sizes of the deflection ellipses were chosen in order to match moment arms in literature (see [Figure S3](#)) and can be found in [Listing S1](#). For more details on this see [Suisa \(2017\)](#). The (non-)muscle-specific parameters can be found in [Table S2](#) and [Table S3](#).

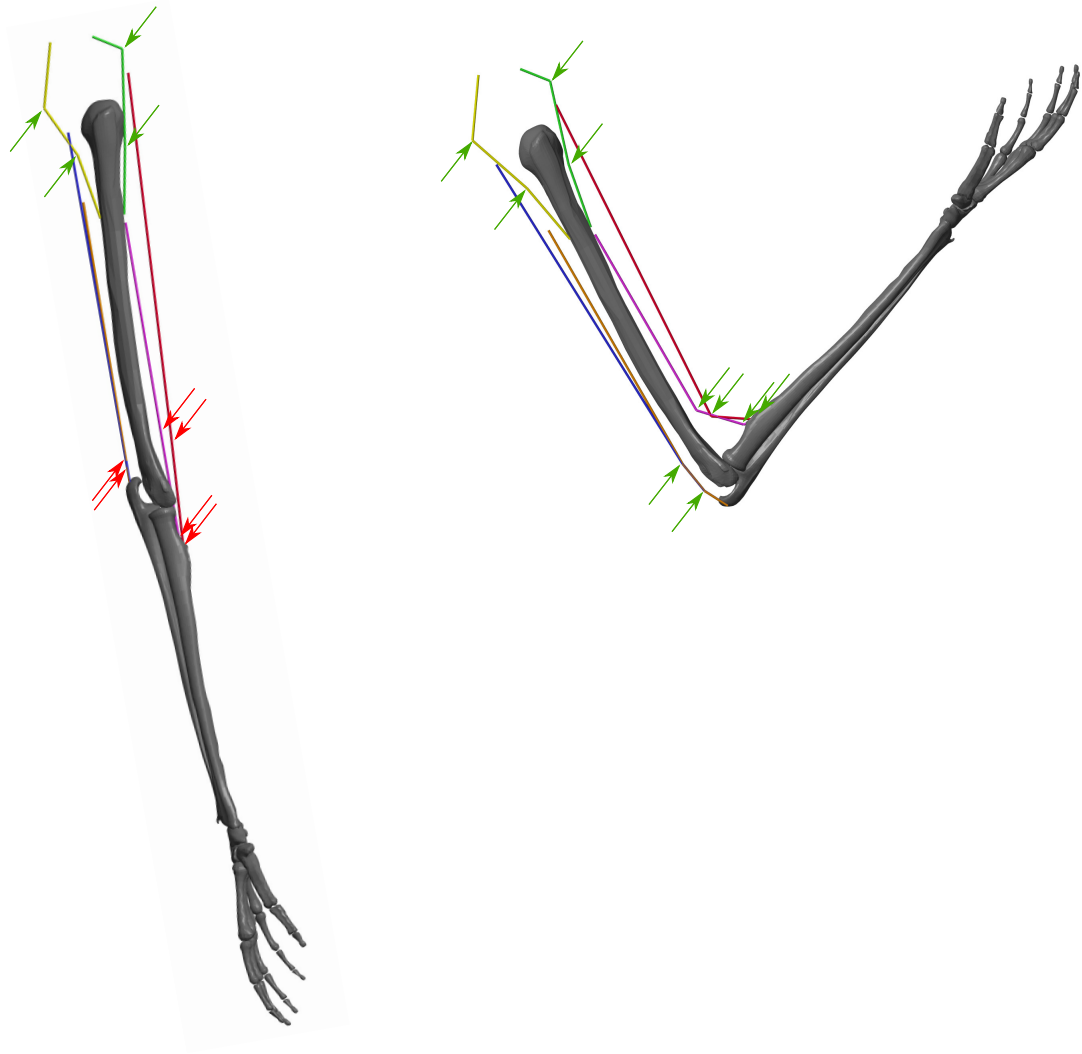


Figure S2: Illustration of the positions of the deflection ellipses that are used for the muscle routing in two different arm positions. Green arrows indicate active ellipses that deflect the muscle path, while red arrows indicate inactive ellipses that do not change the muscle path.

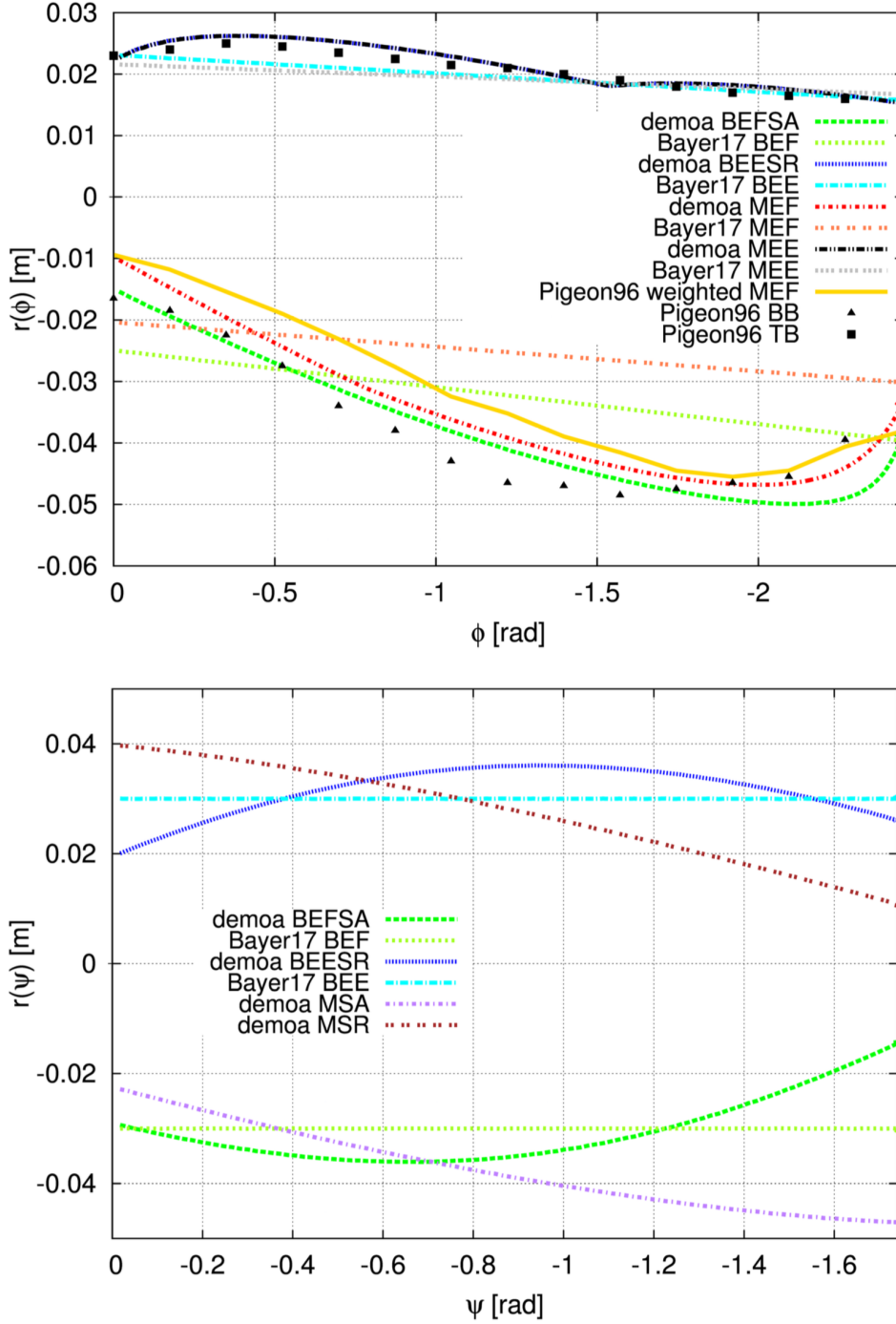


Figure S3: Comparison of the moment arms of the muscles in the model with simulation and experimental data from literature for the elbow muscles (upper plot) and the shoulder muscles (lower plot). The lines marked with "demoa" refer to the model by [Suissa \(2017\)](#) on which our model is based (for the naming of the muscles see [Table S2](#)). We use the same geometry and position and size of the ellipses, so our moment arms are the same as in the "demoa" model. The moment arms are compared to a calculatory model by [Bayer et al. \(2017\)](#) (here M/B stands for mono- and biarticular, E stands for elbow and F/E stands for flexion and extension, respectively) and to experimental data. The black marks show experimental data of the biceps brachii (BB) and the triceps brachii (TB) taken from [Pigeon et al. \(1996\)](#). The yellow line shoes a weighted combination of the monoarticular flexor muscles that are represented by the MEF in the model. They are weighted according to their proportion of the joint torques, see [Sobotta \(2010\)](#); [Aumüller et al. \(2017\)](#). The figure was taken from [Suissa \(2017\)](#) with kind permission of the author.

	Length [m]	d [m]	Mass [kg]	I [kgm ²]	I with exoskeleton [kgms ²]
Upper arm	0.335	0.146	2.10	0.024	0.024
Lower arm	0.263	0.179	1.65	0.025	0.1118

Table S1: Mechanical parameters of the skeletal structure (Kistemaker et al. (2006)) with d =distance from proximal joint to center of mass and I =moment of inertia with respect to the center of mass. Last column: when comparing to experiments, the inertia properties of the lower arm can be adapted according to an arm that is attached to an exoskeleton robot that was used by Bhanpuri et al. (2014).

	F^{\max} [N]	$l^{\text{CE,opt}}$ [m]	$l^{\text{SEE},0}$ [m]
Monarticular Elbow Flexor (MEF)	1420	0.092	0.182
Monarticular Elbow Extensor (MEE)	1550	0.093	0.187
Monoarticular Shoulder Anteversion (MSA)	838	0.134	0.039
Monoarticular Shoulder Retroversion (MSR)	1207	0.140	0.066
Biarticular Elbow Flexor Shoulder Anteversion (BEFSA)	414	0.151	0.245
Biarticular Elbow Extensor Shoulder Retroversion (BEESR)	603	0.152	0.260

Table S2: Muscle-specific actuation parameters (Kistemaker et al. (2006) and Kistemaker et al. (2013)), with F^{\max} : maximum isometric force, $l^{\text{CE,opt}}$: optimal length of the contractile element, $l^{\text{SEE},0}$ rest length of the serial elastic element. The lengths of $l^{\text{CE,opt}}$ and $l^{\text{SEE},0}$ were adapted to match the muscle path routed through the ellipses in order to allow for a big range of motion. For this parameter adaptation method see Suissa (2017).

	Parameter	Unit	Value	Source	Description
CE	ΔW^{des}	[]	0.45	similar to Bayer et al. (2017); Kistemaker et al. (2006)	width of normalized bell curve in descending branch, adapted to match observed force-length curves
	ΔW^{asc}	[]	0.45	similar to Bayer et al. (2017); Kistemaker et al. (2006)	width of normalized bell curve in ascending branch, adapted to match observed force-length curve
	$\nu^{\text{CE,des}}$	[]	1.5	Mörl et al. (2012)	exponent for descending branch
	$\nu^{\text{CE,asc}}$	[]	3.0	Mörl et al. (2012)	exponent for ascending branch
	$A^{\text{rel},0}$	[]	0.2	Günther (1997)	parameter for contraction dynamics: maximum value of A^{rel}
	$B^{\text{rel},0}$	[1/s]	2.0	Günther (1997)	parameter for contraction dynamics: maximum value of B^{rel}
	\mathcal{S}^{ecc}	[]	2.0	van Soest et al. (1993)	relation between $F(v)$ slopes at $v^{\text{CE}} = 0$
	\mathcal{F}^{ecc}	[]	1.5	van Soest et al. (1993)	factor by which the force can exceed F^{isom} for large eccentric velocities
PEE	$\mathcal{L}^{\text{PEE},0}$	[]	0.95	Günther (1997)	rest length of PEE normalized to optimal length of CE
	ν^{PEE}	[]	2.5	Mörl et al. (2012)	exponent of F^{PEE}
	\mathcal{F}^{PEE}	[]	2.0	Mörl et al. (2012)	force of PEE if l^{CE} is stretched to ΔW^{des}
SDE	D^{SDE}	[]	0.3	Mörl et al. (2012)	dimensionless factor to scale $d^{\text{SDE,max}}$
	R^{SDE}	[]	0.01	Mörl et al. (2012)	minimum value of d^{SDE} (at $F^{\text{MTU}} = 0$), normalized to $d^{\text{SDE,max}}$
SEE	$\Delta U^{\text{SEE,nll}}$	[]	0.0425	Mörl et al. (2012)	relative stretch at non-linear linear transition
	$\Delta U^{\text{SEE,l}}$	[]	0.017	Mörl et al. (2012)	relative additional stretch in the linear part providing a force increase of $\Delta F^{\text{SEE},0}$
	$\Delta F^{\text{SEE},0}$	[N]	$0.4 F^{\text{max}}$		both force at the transition and force increase in the linear part
Hatze	m	[1/s]	11.3	Kistemaker et al. (2006)	time constant for the activation dynamics
	c	[mol/l]	1.37e-4	Kistemaker et al. (2006)	constant for the activation dynamics
	η	[l/mol]	5.27e4	Kistemaker et al. (2006)	constant for the activation dynamics
	k	[]	2.9	Kistemaker et al. (2006)	constant for the activation dynamics
	q_0	[]	0.005	Günther (1997)	resting active state for all activated muscle fibers
	ν	[]	3	Kistemaker et al. (2006)	constant for the activation dynamics

Table S3: Muscle non-specific actuation parameters for the muscles and the activation dynamics.

Mechanics parameters defining the geometry and the mechanical properties

```

1  % Gravity
2  PM.Gravity = [0 0 -9.80665];
3
4  %% =====
5  % Segment parameters %
6  %=====
7  PM.SegShoulder.p.Bone.CoM      = [0 0 0]; %[m] position of Bone CoM relative to proximal joint
8  PM.SegShoulder.p.joint_distal = [0 -0.1816 0]; %[m] position of distal joint relative to CoM
9
10 PM.SegShoulder.m.Bone          = 16.895560; %[kg] m
11 PM.SegShoulder.MomInert_Bone   = [0.096243 0.0811621 0.159251]; %[kg*m^2] Diagonal elements of the inertia tensor
12 PM.SegShoulder.ProdInert_Bone  = [0 0 0]; %[kg*m^2] Non-diagonal elements of the inertia tensor in the order [I.yz I.zx I.xy]
13 PM.SegUparm.p.Bone.CoM        = [0 0 0.146]*(-1); %[m] position of Bone CoM relative to proximal joint %*(-1) in comparison with demoa, source: Kistemaker2007
14 PM.SegUparm.p.joint_distal    = [0 0 -0.109]; %[m] position of distal joint relative to CoM
15
16 PM.SegUparm.m.Bone            = 2.10; %[kg] mass, source: Kistemaker2007
17 PM.SegUparm.MomInert_Bone     = [0.0154388 0.024 0.00278951]; %[kg*m^2] Diagonal elements of the inertia tensor
18 PM.SegUparm.ProdInert_Bone    = [0 0 0]; %[kg*m^2] Non-diagonal elements of the inertia tensor in the order [I.yz I.zx I.xy]
19 PM.SegForearm.p.Bone.CoM      = [0 0 0.179]*(-1); %[m] position of Bone CoM relative to proximal joint, source: Kistemaker2007
20 PM.SegForearm.p.joint_distal  = [0 0 -0.084]; %[m] position of distal joint relative to CoM %Note: difference to demoa model, where: [0.015 0 -0.084]
21
22 PM.SegForearm.m.Bone          = 1.65; %[kg] mass, source: Kistemaker2007
23 PM.SegForearm.MomInert_Bone   = [0.009824518 0.025 0.001500813]; %[kg*m^2] Diagonal elements of the inertia tensor
24 PM.SegForearm.ProdInert_Bone  = [0 0 0]; %[kg*m^2] Non-diagonal elements of the inertia tensor in the order [I.yz I.zx I.xy]
25 PM.SegHand.p.Bone.CoM        = [0 0 0.07]*(-1); %[m] position of Bone CoM relative to proximal joint %Note: difference to demoa model, where: [0.015 0.0000 0.07]*(-1)
26 PM.SegHand.p.fingertip       = [0 0 -0.084]; %[m] position of distal joint relative to CoM
27
28 PM.SegHand.m.Bone            = 0; %[kg] m
29 PM.SegHand.MomInert_Bone     = [0 0 0]; %[kg*m^2] Diagonal elements of the inertia tensor
30 PM.SegHand.ProdInert_Bone    = [0 0 0]; %[kg*m^2] Non-diagonal elements of the inertia tensor in the order [I.yz I.zx I.xy]
31
32 %=====
33 % Deflection parameters %
34 %=====
35
36 PM.Deflection.biart_flexor.r0      = [0.03 -0.1816 0.02]; % Origin of the muscle relative to the center of mass of the parent body %Parent: Shoulder
37 PM.Deflection.biart_flexor.rI      = [0.012, 0.0000, 0.12]; % Insertion of the muscle %Parent: Forearm
38 PM.Deflection.biart_flexor.Ellipse1.r = [0.018, 0.0000, -0.1425]; % Coordinates of the reference point of deflection ellipse 1 relative to the parent body %Parent:Uparm
39 PM.Deflection.biart_flexor.Ellipse1.G = [0 1 0]*0.0001; % Length of the half-axis of ellipse 1 in y direction
40 PM.Deflection.biart_flexor.Ellipse1.H = [0 0 1]*0.0001; % Length of the half-axis of ellipse 1 in z direction
41 PM.Deflection.biart_flexor.Ellipse1.angle = [0,90,0]; % Angle [deg] of rotation of the ellipse triade around y-axis to orient the ellipse correctly
42 PM.Deflection.biart_flexor.Ellipse2.r = [0.012, 0.0000, 0.125]; %Parent: Forearm
43 PM.Deflection.biart_flexor.Ellipse2.G = [0 1 0]*0.0001;
44 PM.Deflection.biart_flexor.Ellipse2.H = [0 0 1]*0.0001;
45 PM.Deflection.biart_flexor.Ellipse2.angle = [0,0,0];
46
47 PM.Deflection.biart_extensor.r0      = [-0.02 -0.1816 -0.03]; %Parent: Shoulder
48 PM.Deflection.biart_extensor.rI      = [-0.0225, 0.0000, 0.1925]; %Parent: Forearm
49 PM.Deflection.biart_extensor.Ellipse1.r = [-0.0225, 0.0000, -0.165]; %Parent:Uparm
50 PM.Deflection.biart_extensor.Ellipse1.G = [0 1 0]*0.0001;
51 PM.Deflection.biart_extensor.Ellipse1.H = [0 0 1]*0.0001;
52 PM.Deflection.biart_extensor.Ellipse1.angle = [0,-90,0];
53 PM.Deflection.biart_extensor.Ellipse2.r = [-0.0, 0.0000, 0.1975]; %Parent: Forearm
54 PM.Deflection.biart_extensor.Ellipse2.G = [0 1 0]*0.0001;
55 PM.Deflection.biart_extensor.Ellipse2.H = [0 0 1]*0.03;
56 PM.Deflection.biart_extensor.Ellipse2.angle = [0,-60,0];
57
58 PM.Deflection.Shoulder_Anteversion.r0 = [0.00, -0.1816, 0.05]; %Parent: Shoulder
59 PM.Deflection.Shoulder_Anteversion.rI = [0.01, 0.0000, 0.045]; %Parent:Uparm
60 PM.Deflection.Shoulder_Anteversion.Ellipse1.r = [0.025, -0.1816, 0.04]; %Parent: Shoulder
61 PM.Deflection.Shoulder_Anteversion.Ellipse1.G = [0 1 0]*0.0001;
62 PM.Deflection.Shoulder_Anteversion.Ellipse1.H = [0 0 1]*0.0001;
63 PM.Deflection.Shoulder_Anteversion.Ellipse1.angle = [0,0,0];
64 PM.Deflection.Shoulder_Anteversion.Ellipse2.r = [0.02, 0.0000, 0.1]; %Parent:Uparm
65 PM.Deflection.Shoulder_Anteversion.Ellipse2.G = [0 1 0]*0.0001;
66 PM.Deflection.Shoulder_Anteversion.Ellipse2.H = [0 0 1]*0.0001;
67 PM.Deflection.Shoulder_Anteversion.Ellipse2.angle = [0,90,0];
68
69 PM.Deflection.Shoulder_Retroversion.r0 = [-0.035, -0.1816, 0.045]; %Parent: Shoulder
70 PM.Deflection.Shoulder_Retroversion.rI = [-0.01, 0.0000, 0.045]; %Parent:Uparm
71 PM.Deflection.Shoulder_Retroversion.Ellipse1.r = [-0.04, -0.1816, -0.01]; %Parent: Shoulder
72 PM.Deflection.Shoulder_Retroversion.Ellipse1.G = [0 1 0]*0.0001;
73 PM.Deflection.Shoulder_Retroversion.Ellipse1.H = [0 0 1]*0.0001;
74 PM.Deflection.Shoulder_Retroversion.Ellipse1.angle = [0,0,0];
75 PM.Deflection.Shoulder_Retroversion.Ellipse2.r = [-0.02, 0.0000, 0.1]; %Parent:Uparm
76 PM.Deflection.Shoulder_Retroversion.Ellipse2.G = [0 1 0]*0.0001;
77 PM.Deflection.Shoulder_Retroversion.Ellipse2.H = [0 0 1]*0.0001;
78 PM.Deflection.Shoulder_Retroversion.Ellipse2.angle = [0,90,0];
79
80 PM.Deflection.Elbow_flexor.r0      = [0.01, 0.0000, 0.038]; %Parent:Uparm
81 PM.Deflection.Elbow_flexor.rI      = [0.01, 0.0000, 0.12]; %Parent: Forearm
82 PM.Deflection.Elbow_flexor.Ellipse1.r = [0.0, 0.0000, -0.132]; %Parent:Uparm
83 PM.Deflection.Elbow_flexor.Ellipse1.G = [0 1 0]*0.0001;
84 PM.Deflection.Elbow_flexor.Ellipse1.H = [0 0 1]*0.005;

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85 PM.Deflection.Elbow_flexor.Ellipse1.angle = [0,90,0];
86 PM.Deflection.Elbow_flexor.Ellipse2.r = [0.01, 0.0000, 0.135]; %Parent: Forearm
87 PM.Deflection.Elbow_flexor.Ellipse2.G = [0 1 0]*0.0001;
88 PM.Deflection.Elbow_flexor.Ellipse2.H = [0 0 1]*0.003;
89 PM.Deflection.Elbow_flexor.Ellipse2.angle = [0,90,0];
90
91 PM.Deflection.Elbow_extensor.r0 = [-0.022, 0.0000, 0.0605]; %Parent:Uparm
92 PM.Deflection.Elbow_extensor.r1 = [-0.0225, 0.0000, 0.1925]; %Parent: Forearm
93 PM.Deflection.Elbow_extensor.Ellipse1.r = [-0.0225, 0.0000, -0.165]; %Parent:Uparm
94 PM.Deflection.Elbow_extensor.Ellipse1.G = [0 1 0]*0.0001;
95 PM.Deflection.Elbow_extensor.Ellipse1.H = [0 0 1]*0.00005;
96 PM.Deflection.Elbow_extensor.Ellipse1.angle = [0,-90,0];
97 PM.Deflection.Elbow_extensor.Ellipse2.r = [-0.0, 0.0000, 0.1975]; %Parent: Forearm
98 PM.Deflection.Elbow_extensor.Ellipse2.G = [0 1 0]*0.0001;
99 PM.Deflection.Elbow_extensor.Ellipse2.H = [0 0 1]*0.03;
100 PM.Deflection.Elbow_extensor.Ellipse2.angle = [0,-60,0];

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Listing S1: Mechanics parameters defining the geometry and the mechanical properties.

List of Abbreviations

MTU	muscle-tendon unit
CE	contractile element
PEE	parallel elastic element
SEE	serial elastic element
SDE	serial damping element
EF	Elbow Flexor
MEF	Monarticular Elbow Flexor
EE	Elbow Extensor
MEE	Monarticular Elbow Extensor
BF	Biarticular Flexor
BEFSA	Biarticular Elbow Flexor Shoulder Anteversion
BE	Biarticular Extensor
BEESR	Biarticular Elbow Extensor Shoulder Retroversion
SF	Shoulder Flexor
MSA	Monoarticular Shoulder Anteversion
SE	Shoulder Extensor
MSR	Monoarticular Shoulder Retroversion

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