

A statistical shape model of the tibia-fibula complex: sexual dimorphism and effects of age on reconstruction accuracy from anatomical landmarks

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Supplementary Information

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Bone(s)	Region	RMSE (mm)			Max (mm)			Jaccard		
		Scale	9 landmarks	14 landmarks	Scale	9 landmarks	14 landmarks	Scale	9 landmarks	14 landmarks
Tibia-fibula	All	1.78 (0.62)	1.62 (0.35) *	1.51 (0.29) *‡	5.84 (2.62)	5.12 (1.64) *	4.82 (1.25) *	0.792 (0.077)	0.824 (0.038) *	0.833 (0.034) *‡
Tibia	All	1.75 (0.72)	1.56 (0.43)*	1.39 (0.28)*‡	5.42 (2.77)	4.86 (1.74) *	4.57 (1.21) *	0.835 (0.068)	0.852 (0.043) *	0.866 (0.035) *‡
	Proximal	1.79 (0.67)	1.51 (0.42)*	1.39 (0.33)*‡	5.11 (1.72)	4.41 (1.65) *	4.1 (1.27) *			
	Diaphysis	1.56 (0.75)	1.41 (0.49)*	1.32 (0.35)*‡	3.73 (1.43)	3.58 (1.28) *	3.09 (1.10) *			
	Distal	1.73 (1.08)	1.35 (0.63)*	1.34 (0.52)*	4.53 (2.84)	4.13 (1.64) *	3.94 (1.50) *			
Fibula	All	1.77 (0.62)	1.54 (0.51) *	1.51 (0.38) *‡	5.05 (1.77)	4.57 (1.29) *	5.59 (1.25) *	0.627 (0.114)	0.688 (0.122) *	0.695 (0.091) *‡
	Proximal	1.97 (0.69)	1.66 (0.54) *	1.67 (0.57) *	4.73 (1.62)	4.32 (1.38) *	4.26 (1.26) *			
	Diaphysis	1.67 (0.58)	1.45 (0.64) *	1.41 (0.45) *‡	3.83 (1.65)	3.82 (1.25) *	3.5 (0.98) *			
	Distal	1.57 (0.72)	1.4 (0.50) *	1.38 (0.42) *	3.76 (1.80)	3.66 (1.56) *	3.39 (1.43) *			

Table S1: Median (IQR) reconstruction error measures, calculated for the whole bone (all), or specific regions. Proximal is 0-20%, diaphysis is 20-80%, and distal is 80-100% of the length of the tibia or fibula. All Friedman ANOVAs except the proximal fibula maximum error were significant at family-wise error of $p < 0.05$ (critical $p = 0.017$). * significant difference to isometric scaling at family-wise $p < 0.05$ (critical $p = 0.006$). ‡ significant difference between 9 and 14 landmark reconstructions at family-wise $p < 0.05$ (critical $p = 0.006$).

Bone(s)	Region	RMSE (mm)			Max (mm)			Jaccard		
		Scale	9 landmarks	14 landmarks	Scale	9 landmarks	14 landmarks	Scale	9 landmarks	14 landmarks
Tibia-fibula	All ^{a,b,c}	2.78 (0.63)	2.11 (0.31)	2.17 (0.34)	9.22 (2.36)	6.91 (1.00) *	7.04 (1.03) *	0.672 (0.024)	0.769 (0.010) *	0.763 (0.012) *
Tibia	All ^{a,b,c}	3.03 (0.69)	2.15 (0.30) *	2.17 (0.33) *	9.16 (2.35)	6.69 (0.98) *	6.98 (1.08) *	0.699 (0.023)	0.799 (0.010) *	0.796 (0.012) *
	Proximal ^{a,b}	3.46 (0.86)	2.34 (0.28) *	2.38 (0.34) *	9.16 (2.35)	6.68 (0.99) *	6.85 (1.10) *			
	Diaphysis ^a	2.25 (0.66)	1.94 (0.42)	1.93 (0.38)	6.09 (1.72)	4.75 (0.98)	4.58 (0.62)			
	Distal ^a	3.07 (0.68)	2.15 (0.37) *	2.22 (0.38) *	6.77 (1.59)	5.69 (0.78)	5.84 (0.93)			
Fibula	All	2.24 (0.59)	2.01 (0.40)	2.13 (0.50)	7.34 (2.16)	6.02 (1.05)	6.25 (0.97)	0.526 (0.037)	0.608 (0.020)	0.596 (0.022)
	Proximal ^b	2.55 (0.87)	1.97 (0.42)	2.00 (0.48)	6.84 (2.55)	4.76 (1.07)	4.76 (1.05)			
	Diaphysis	2.09 (0.66)	1.91 (0.48)	2.03 (0.68)	4.75 (1.34)	4.33 (1.15)	4.62 (1.47)			
	Distal	2.24 (0.55)	2.21 (0.48)	2.37 (0.46)	6.17 (1.61)	5.89 (1.13)	5.94 (1.09)			

Table S2: Mean (SD) reconstruction error measures, calculated for the whole bone (all), or specific regions. Proximal is 0-20%, diaphysis is 20-80%, and distal is 80-100% of the length of the tibia or fibula. a (RMSE), b (Max Error), c (Jaccard Index): significant ANOVA at a family-wise error of $p < 0.05$ (critical $p = 0.017$). * significant difference to isometric scaling at family-wise $p < 0.05$ (critical $p = 0.006$). No significant difference between 9 and 14 landmark reconstructions at family-wise $p < 0.05$ (critical $p = 0.006$).

muscle	Young Adults			Old Adults		
	scale	9 landmarks	14 landmarks	scale	9 landmarks	14 landmarks
All muscle points RMSE	5.79 (2.10)	5.98 (3.62)	5.36 (2.73) ‡	11.67 (4.55)	11.97 (3.84)	12.40 (3.44)
Semimembranosus	4.56 (2.84)	4.26 (3.08)	3.41 (2.36)	7.23 (5.86)	7.53 (6.33)	4.99 (6.39)
Semitendinosus	3.89 (2.12)	4.27 (2.83)	4.02 (3.16)	7.08 (4.16)	8.83 (5.63)	7.47 (5.52)
Biceps femoris long head	4.20 (2.89)	3.57 (2.04)	3.69 (2.21)	4.03 (3.19)	4.12 (2.49)	3.51 (1.60)
Biceps femoris short head	4.82 (2.89)	3.73 (2.42)	3.98 (2.58)	4.07 (3.27)	3.88 (1.94)	4.10 (1.16)
Sartorius	5.37 (3.28)	5.33 (4.35)	4.36 (3.90)	9.13 (6.59)	10.22 (6.43)	9.20 (7.01)
Tensor fasciae latae	3.21 (2.51)	2.99 (2.66)	2.83 (2.41)	7.31 (2.61)	6.23 (2.48)	6.08 (1.57)
Gracilis	3.65 (2.06)	4.03 (2.56)	3.41 (2.20)	6.68 (3.80)	7.02 (6.81)	6.53 (5.56)
Soleus	3.47 (1.92)	3.76 (3.41)	3.38 (2.36)	9.95 (6.11)	11.46 (6.77)	11.58 (6.11)
Tibialis posterior	4.58 (3.00)	5.10 (5.09)	4.69 (4.74)	17.20 (8.13)	17.39 (6.26)	18.49 (8.06)
Flexor digitorum	5.04 (3.92)	5.32 (6.65)	4.75 (4.65)	14.10 (9.34)	11.22 (12.97)	13.09 (8.63)
Flexor hallucis	7.85 (6.14)	7.52 (6.67)	6.10 (5.32)	10.02 (6.80)	10.48 (7.32)	10.89 (10.88)
Tibialis anterior	5.74 (4.61)	5.61 (4.15)	5.41 (4.11)	21.68 (10.84)	20.00 (14.20)	19.34 (14.37)
Peroneus brevis	8.04 (3.92)	6.54 (6.12)	6.29 (4.50)	5.14 (8.89)	5.55 (10.75)	5.59 (8.39)
Peroneus longus	5.12 (5.06)	6.64 (7.04)	3.91 (3.88)	9.59 (11.47)	7.90 (12.18)	14.62 (15.52)
Peroneus tertius	7.52 (5.16)	6.04 (7.43)	6.57 (4.20)	5.67 (13.80)	6.37 (16.11)	5.61 (12.72)
Extensor digitorum	4.62 (4.16)	6.06 (5.63)	4.27 (4.19)	8.48 (10.01)	6.52 (11.06)	13.67 (11.68)
Extensor hallucis	5.09 (5.43)	6.46 (6.55)	4.54 (4.84)	7.34 (13.63)	5.59 (12.52)	12.72 (15.56)
Patellar ligament	3.95 (2.23)	4.35 (3.22)	3.79 (2.55)	7.71 (3.50)	8.36 (7.20)	7.48 (4.91)

Table S3: Median (IQR) Euclidian distance (mm) between muscle points on reconstructed and CT surfaces. ‡ significant difference between 9 and 14 landmark reconstructions for RMSE. No difference between SSM and isometric scaling for RMSE of muscle points. No difference between any reconstruction method for older adults. Highlighted muscles result in non-zero moment arm differences.

Muscle	Young Adults			Old Adults		
	Scale	9 Landmarks	14 Landmarks	Scale	9 Landmarks	14 Landmarks
Semimembranosus ^a	3.47 (2.65)	3.09 (2.24)	2.61 (1.46) *‡	8.33 (4.92)	7.98 (6.02)	7.49 (3.58)
Biceps Femoris Long Head ^a	3.65 (2.90)	2.36 (1.90) *	2.45 (2.08) *	5.99 (6.43)	4.76 (5.74)	5.99 (5.12)
Biceps Femoris Short Head ^a	3.99 (3.14)	3.01 (2.06) *	2.74 (2.34) *	7.25 (8.20)	6.04 (7.12)	6.79 (6.52)
Tensor Fasciae Latae	0.66 (0.73)	0.63 (0.76)	0.60 (0.80)	1.02 (0.98)	1.02 (1.54)	1.32 (1.01)
Soleus	0.13 (0.15)	0.09 (0.17)	0.10 (0.16)	0.27 (0.30)	0.25 (0.43)	0.31 (0.37)
Patellar Ligament	0.41 (0.41)	0.44 (0.60)	0.40 (0.55)	1.10 (1.38)	0.71 (0.93)	0.70 (1.27)

Table S4: Median (IQR) of maximum difference (mm) in moment arm compared to CT-based subject-specific model through physiologic range of motion. ^a Freidman’s ANOVA significant for the young adult group. ^b Repeated measures ANOVA significant for the old adult group. * significant difference to isometric scaling at family-wise $p < 0.05$ (critical $p = 0.008$). ‡ significant difference between 9 and 14 landmark reconstructions.

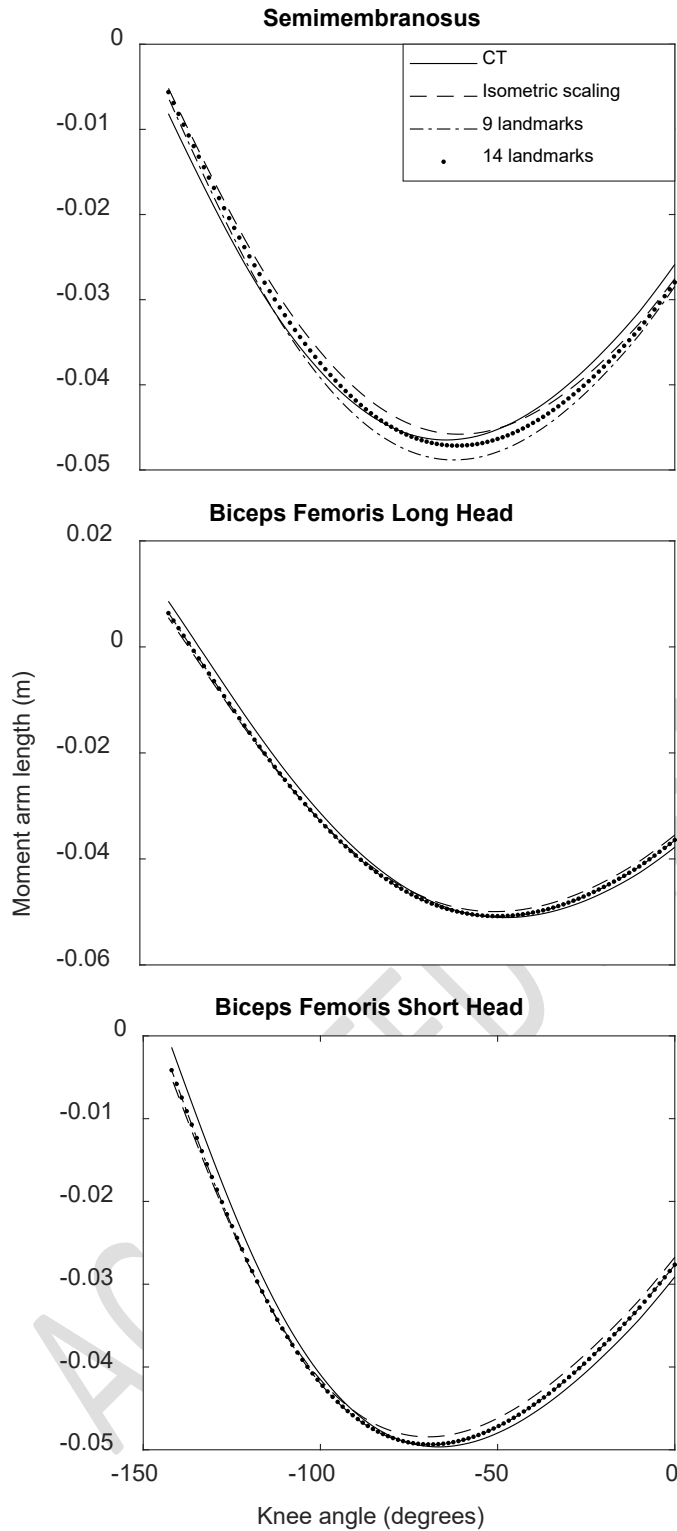


Figure S1: Comparison of muscle moment arms in the sagittal plane as a function of knee angle between models defined by CT, isometrically scaled average, and SSM reconstructed geometries (representative example).