

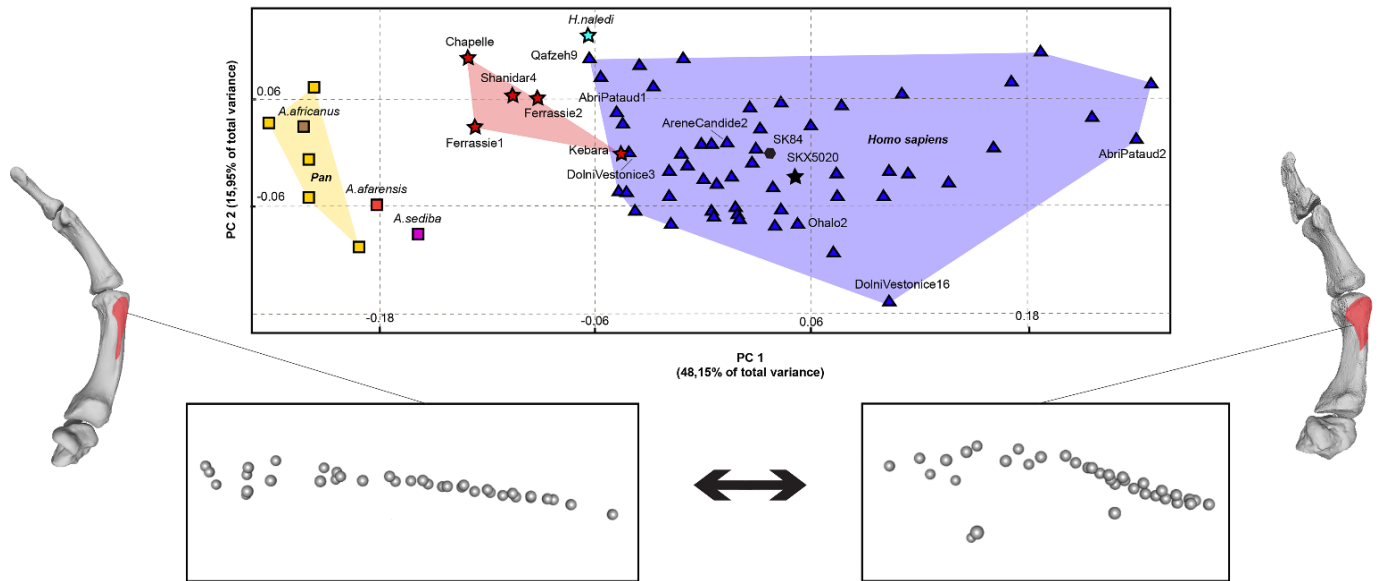
Current Biology, Volume 31

Supplemental Information

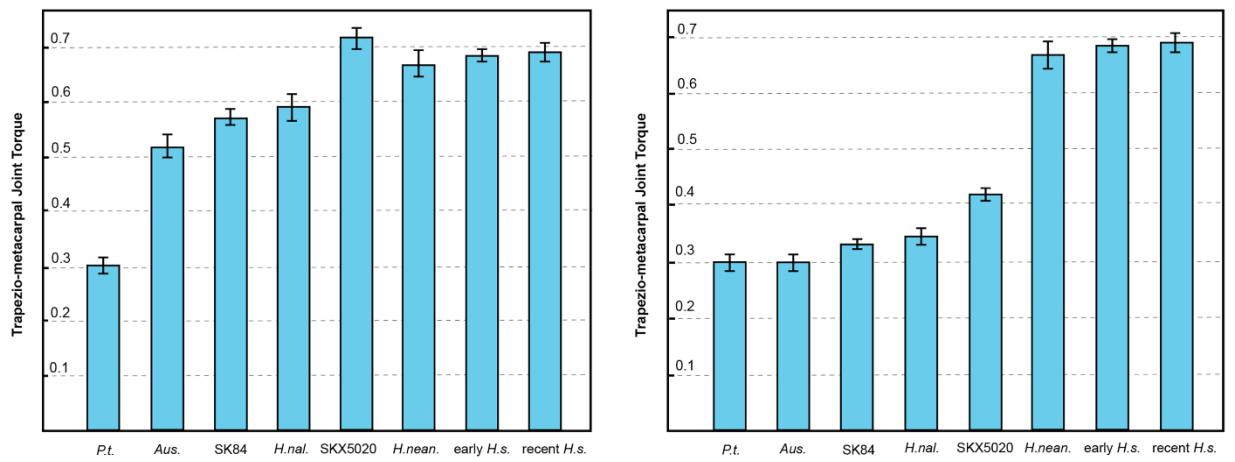
Biomechanics of the human thumb and the evolution of dexterity

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A



B



C

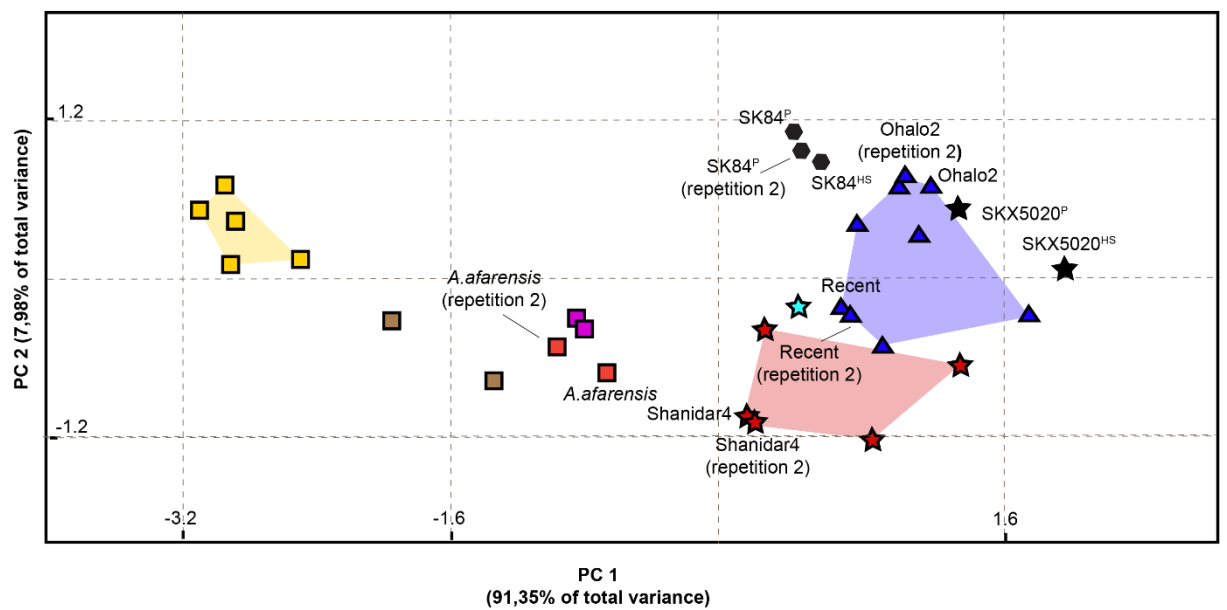


Figure S1. Composite plot presenting the three-dimensional geometric morphometric analysis of muscle attachment shape (A), graphic summary of torque variables (B), and results of the inter-observer precision test (C). Related to Figures 1 to 3, Table S3, and Video S1. (A) Plot of the shape principal component analysis on the metacarpal enthesis of *m. opponens pollicis*. The side figures represent 3D shape changes associated with variation along the first principal component, describing proportional bone projection across the muscle attachment site. It should be mentioned that the observed relative projection occurs mostly at the distal portion of the enthesis (closer to the metacarpal head). (B) Bar charts summarizing the sample's variation across groups/specimens in average torque (i.e., “grand mean” values, see Table S3), under the assumption of either a human (left) or a chimpanzee (right) muscle force-generating capacity for the earlier hominins (see Figure 1 and Video S1). Each bar chart indicates the mean value and its standard error, while the respective standard deviations are listed in Table S3. Figure abbreviations: *Australopithecus* (*Aus.*); *Homo naledi* (*H.n.*), Neanderthals (*H.nean.*), *Homo sapiens* (*H.s.*), and *Pan troglodytes* (*P.t.*). (C) Precision analysis: plot of the principal component analysis (muscle paradigm 1) with the projected scores of the five specimens selected for the double-blind inter-observer repeatability analysis. Original and second measurements are labeled in the plot. The difference between the two repetitions do not considerably affect the observed differences among hominin groups. In specimen labels, the superscript “P” indicates that a chimp trapezium was used in the model, while the superscript “HS” refers to the use of a modern human trapezium (see STAR Methods).

Analyses	Eigenvalue	Variance explained (%)	Factor loadings			
Before size-adjustment			13-1	13-2	13-3	sPC1
PC1	3.57	91.35	0.99	0.99	0.98	0.87
PC2	0.39	7.98	-0.16	-0.09	-0.19	0.5
Total		99.33				
After size-adjustment						
PC1	3.63	90.66	0.98	0.99	0.98	0.86
PC2	0.34	8.55	-0.18	-0.06	-0.21	0.51
Total		99.22				

Table S1. Statistics of the four principal component analyses (PCAs), corresponding to the four muscle paradigms utilized (see STAR Methods). Related to Figures 2 and 3.

Paradigm	PCSA	$F_{\max}$	F_M (mean $\pm$ standard deviation)
Paradigm 1: Human PCSA	2.63 cm ²	66 N	(63.8 $\pm$ 1.4) N
Paradigm 2: Chimpanzee PCSA	1.55 cm ²	39 N	(37.654 $\pm$ 0.63) N
Paradigm 3: Normalized human PCSA	-	1	0.966 $\pm$ 0.018
Paradigm 4: Normalized chimpanzee PCSA	-	0.59	0.5688 $\pm$ 0.0096

Table S2. Summary of the muscle parameters used in the models of the present study. Related to Figure 1.

Group / Specimen	MP	Torques									Grand Mean	TTL
		L1-L4	L2-L4	L3-L4	L1-L5	L2-L5	L3-L5	L1-L6	L2-L6	L3-L6		
Aus.	H.s	0.53±0.05	0.50±0.06	0.55±0.05	0.59±0.05	0.56±0.06	0.60±0.05	0.45±0.05	0.42±0.05	0.47±0.05	0.52±0.06	0.67±0.01
	P.t.	0.32±0.03	0.28±0.04	0.34±0.05	0.34±0.03	0.31±0.05	0.35±0.04	0.26±0.03	0.22±0.02	0.29±0.04	0.30±0.04	0.39±<0.01
SK84	H.s	0.60±<0.01	0.55±<0.01	0.62±<0.01	0.61±<0.01	0.57±<0.01	0.62±<0.01	0.53±<0.01	0.51±<0.01	0.55±<0.01	0.57±0.04	-
	P.t.	0.35±<0.01	0.32±0.01	0.36±0.01	0.36±0.03	0.33±0.03	0.37±0.03	0.31±0.01	0.29±0.01	0.32±0.01	0.33±0.03	-
SKX5020	H.s	0.76±0.07	0.72±0.06	0.75±0.07	0.78±0.01	0.75±0.01	0.76±0.01	0.65±0.07	0.64±0.08	0.64±0.07	0.72±0.06	-
	P.t.	0.45±0.04	0.43±0.03	0.44±0.04	0.46±0.01	0.44±<0.01	0.45±0.01	0.38±0.04	0.37±0.04	0.38±0.04	0.42±0.04	-
H.n.	H.s	0.70	0.57	0.69	0.57	0.47	0.56	0.63	0.52	0.61	0.59±0.08	0.76±0.09
	P.t.	0.41	0.34	0.41	0.34	0.28	0.33	0.37	0.30	0.36	0.35±0.04	0.45±0.06
H.nean.	H.s	0.74±0.06	0.66±0.07	0.75±0.06	0.73±0.01	0.61±0.05	0.73±0.01	0.63±0.07	0.55±0.08	0.63±0.07	0.67±0.07	0.71±0.07
early H.s.	H.s	0.70±0.04	0.68±0.02	0.71±0.05	0.72±0.01	0.70±0.01	0.72±0.02	0.65±0.08	0.63±0.06	0.66±0.09	0.69±0.03	0.72±0.03
recent H.s.	H.s	0.70±0.06	0.69±0.06	0.70±0.06	0.76±0.06	0.73±0.06	0.75±0.06	0.64±0.05	0.62±0.05	0.63±0.05	0.69±0.05	0.74±0.05
P.t.	P.t.	0.32±0.03	0.28±0.04	0.34±0.05	0.34±0.03	0.31±0.05	0.35±0.04	0.26±0.03	0.22±0.02	0.29±0.04	0.30±0.04	0.34±0.05

Table S3. Descriptive statistics (means ± standard deviations) for the nine torque variables developed, separated by group and muscle paradigm (MP). Related to Figures 1 and 2. MP involves the muscle force-generating capacity of either *Homo sapiens* (“*H.s.*”) or chimpanzees (“*P.t.*”). For facilitating comparisons, the table includes the grand mean (and its standard deviation) for each group / specimen. The latter variable is also graphically summarized in Figure S1B, which includes the grand means’ standard error. The rightmost column represents the mean “torque to thumb length index” (TTL), which was calculated by dividing all computed torque values by the corresponding thumb length (in mm) and then multiplying the result by 100 (see STAR Methods). Table abbreviations: *Australopithecus* (*Aus.*); *Homo naledi* (*H.n.*), Neanderthals (*H.nean.*), *Homo sapiens* (*H.s.*), and *Pan troglodytes* (*P.t.*).

Landmark	Bone	Description
L1	Metacarpal	Most projecting point of the enthesis
L2	Metacarpal	Most proximal point of the enthesis
L3	Metacarpal	Most distal point of the enthesis
L4	Trapezium	Most projecting central point of the enthesis
L5	Trapezium	Midway between the most projecting point and the medial border of the enthesis
L6	Trapezium	Midway between the most projecting point and the lateral border of the enthesis
L7	Metacarpal	Most palmar point of the enthesis
L8	Metacarpal	Most dorsal point of the enthesis
L9	Metacarpal	Medial angle separating the enthesis into a proximal elongated portion and a distal tubercle
L10	Metacarpal	Lateral angle separating the enthesis into a proximal elongated portion and a distal tubercle

Table S4. Definitions of the fixed 3D landmarks used in the biomechanical models and the geometric morphometric analysis. Related to Figures 1 to 3.

	Torque pairs		r-value	p-value
Modern human muscle paradigm	L1-L4	L1-L5	0.82	< 0.001
	L1-L4	L1-L6	0.92	< 0.001
	L1-L5	L1-L6	0.83	< 0.001
	L2-L4	L2-L5	0.87	< 0.001
	L2-L4	L2-L6	0.94	< 0.001
	L2-L5	L2-L6	0.90	< 0.001
	L3-L4	L3-L5	0.84	< 0.001
	L3-L4	L3-L6	0.91	< 0.001
	L3-L5	L3-L6	0.84	< 0.001
Chimpanzee muscle paradigm	L1-L4	L1-L5	0.83	< 0.001
	L1-L4	L1-L6	0.94	< 0.001
	L1-L5	L1-L6	0.80	< 0.001
	L2-L4	L2-L5	0.84	< 0.001
	L2-L4	L2-L6	0.94	< 0.001
	L2-L5	L2-L6	0.84	< 0.001
	L3-L4	L3-L5	0.83	< 0.001
	L3-L4	L3-L6	0.94	< 0.001
	L3-L5	L3-L6	0.81	< 0.001

Table S5. Spearman’s bivariate correlations among the nine torque calculations. Related to Figure 1. Each torque variable is represented by its corresponding pair of landmarks (L) utilized in the models for the muscle’s origin and insertion points (see Table S4). The p-values maintained their significance (p-value < 0.05) after Holm-Bonferroni correction.

Analysis	p-value	F-value	R ²	Model / Torque correlations (r-values)		
				13-1	13-2	13-3
Modern human muscle paradigm	<0.01	10.59	0.53	0.74	0.74	0.71
<i>Pan</i> muscle paradigm	0.01	4.79	0.27	0.52	0.54	0.49
Size-adjusted modern human muscle paradigm	<0.01	7.17	0.41	0.65	0.66	0.61
Size-adjusted <i>Pan</i> muscle paradigm	<0.01	7.49	0.26	0.51	0.55	0.46

Table S6. Results of the four multivariate regression analyses (one for each paradigm; see STAR Methods) revealing a strong correlation between three torque calculations and 3D proportional bone projection at muscle attachment surfaces. Related to Figure 1. The presented statistics include statistical significance of the model (p-value and F-value), proportion of torque variance explained by enthesal projection (R²), and correlation coefficients between the predictive model and each torque variable.