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THE FURCULA IN *SUCHOMIMUS TENERENSIS* AND *TYRANNOSAURUS REX* (DINOSAURIA: THEROPODA: TETANURAE)

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INTRODUCTION

OSSIFIED CLAVICLES, either as paired elements or as a median furcula, have been recorded in all major clades of dinosaurs, including ornithischians, sauropodomorphs, and theropods (Bryant and Russell, 1993). Nearly all but the most basal theropods, *Eoraptor lunensis* and *Herrerasaurus ischigualastensis*, have an ossified furcula including coelophysids (Downs, 2000; Tykoski et al., 2002; Carrano et al., 2005), allosauroids (Chure and Madsen, 1996), tyrannosaurids (Makovicky and Currie, 1998; Larson and Donnan, 2002; Brochu, 2003; Lipkin and Sereno, 2004; Larson and Rigby, 2005), therizinosaurids (Xu et al., 1999a; Zhang et al., 2001), oviraptorids (Barsbold, 1983; Clark et al., 1999, 2001; Hwang et al., 2002; Osmólska et al., 2004), troodontids (Xu and Norell, 2004), and dromaeosaurids (Norell et al., 1997; Norell and Makovicky, 1999; Xu et al., 1999b; Burnham et al., 2000; Hwang et al., 2002). No ossification of any element beyond the coracoid has been found in the pectoral girdle of the well-preserved primitive theropods, *Eoraptor lunensis* and *Herrerasaurus ischigualastensis*.

Although the furcula in tyrannosaurids has been described in several genera (Makovicky and Currie, 1998), the bone has never been found in articulation in any species, and controversy has surrounded the form of the furcula in *Tyrannosaurus rex* (Larson and Donnan, 2002; Brochu, 2003). We describe the furcula in the spinosaurid, *Suchomimus tenerensis*, which aids in establishing the basal condition of this bone for tetanuran theropods. We then describe furculae in *Tyrannosaurus rex*, one of which is preserved in articulation and others of which highlight important variation.

The specimens in this study are housed in the Children's Museum of Indianapolis (CMI), Field Museum (FMNH), Musée National du Niger (MNN), Museum of the Rockies (MOR), and the University of Chicago Research Collection (UCRC).

DESCRIPTION

Suchomimus tenerensis.—A furcula was recovered in a partially articulated skeleton (MNN GAD513) of the spinosaurid *Suchomimus tenerensis* (Sereno et al., 1998). The presacral vertebral column was preserved in articulation, whereas the furcula, ribs, gastralia, girdles, and limbs were disarticulated but in close association. The furcula is V-shaped in anterior view with an intrafurcular angle of 111° (Fig. 1; Table 1). A dorsoventrally-flattened, tongue-shaped hypocleideum projects ventrally in the midline (Fig. 2.1). In anterior view, the hypocleideum is gently concave and displaced somewhat to the left of the midline. The absence of articular rugosities on the hypocleideum suggests that it did not contact other elements of the pectoral girdle. The central ramus has a D-shape in cross-section; anterior and posterior surfaces are convex and nearly flat, respectively (Figs. 1, 2).

The proximal half of each clavicular ramus tapers in dorsoventral width at mid length before expanding as a tongue-shaped epicleideal process (Fig. 1). With the central body held vertically, the epicleideal processes arch gently posteriorly and are marked by striations both anteriorly and posteriorly. The dorsal two-thirds of the epicleideal process is thin; the ventral one-third is thickened posteriorly to form an articular platform for the edge of the acromion. This portion of the process is more strongly fluted for ligament attachment (Fig. 2.2).

Tyrannosaurus rex.—The only undisputed furcula of *Tyrannosaurus rex* belongs to an articulated postcranial skeleton (UCRC V1) preserved in a large sandstone concretion from the Lance Formation (Maastrichtian) of eastern Wyoming (Lipkin and Sereno, 2004). The bones of the trunk are preserved in articulation with little transverse or dorsoventral distortion. The furcula is preserved in situ between the right and left coracoids with each clavicular ramus laying near the acrominal process of the scapula (Fig. 3). The distal ends of both clavicular rami are broken away at the edge of the concretion.

The furcula is U-shaped or, more precisely, lyre-shaped in anterior view with an intrafurcular angle of 71° (Table 1). Unlike other theropod furculae, there is a transversely oriented central body from which extend the clavicular rami (Fig. 4.1). Dorsal and ventral margins of the central body are rounded with no development of a hypocleideal process. The anterior surface has a shallow transverse fossa, whereas the posterior surface is flat. The laterally deflected epicleideal process is preserved on the right side near the acromion of the right scapula. The internal bone texture of the furcula is dense without any development of marrow or pneumatic cavities. This furcula (UCRC V1) most closely resembles that of *Gorgosaurus* (Makovicky and Currie, 1998, figs. 1, 2), which also lacks any development of a hypocleideum, A rudimentary hypocleideum, in contrast, was reported in specimens referred to the tyrannosaurids *Albertosaurus* and *Daspletosaurus* (Makovicky and Currie, 1998, figs. 1, 2).

Another nearly complete furcula (MOR 980) was recovered with a partial skeleton of *T. rex*. MOR 980 was collected from the upper Hell Creek Formation (uppermost Maastrichtian), east of Fort Peck Lake in Montana (Derstler, 2005). This furcula is U-shaped with an intrafurcular angle of 87° (Fig. 4.2; Table 1). The central body has a maximum anteroposterior thickness of 19 mm, which is thicker than the others described herein. The unusual thickness is due to pathology on the left posterior-side of the central body. The pathology may have extended all the way up to the dorsal tip of the left epicleideal process. However, the anterior-side of the furcula is missing the outer portion of the clavicular ramus but the epicleideal process is preserved, and it is also pathologic. The right side of the furcula appears to be free of pathology.

Brochu (2003:95, fig. 84) tentatively identified an elongated shaft with a broken end as a ''partial furcula'' from a well preserved skeleton of *T. rex* (FMNH PR2081; Fig. 5). He noted its similarity to elements from the gastral basket, which we suggest here, is the correct identification. A bone from the same specimen was tentatively regarded as the proximal portion of a posteriormost dorsal rib (Brochu, 2003, fig. 77). The bone, however, does not match the form of more anterior dorsal ribs or the articular facets on the posteriormost dorsal vertebra. We concur with Larson and Rigby (2005, page 253) that this bone (Fig. 4.3) is a partial furcula, which is very similar in size and form to a fourth furcula found in association with another skeleton of *T. rex* (CMI 2001.90.1; Fig. 4.4).

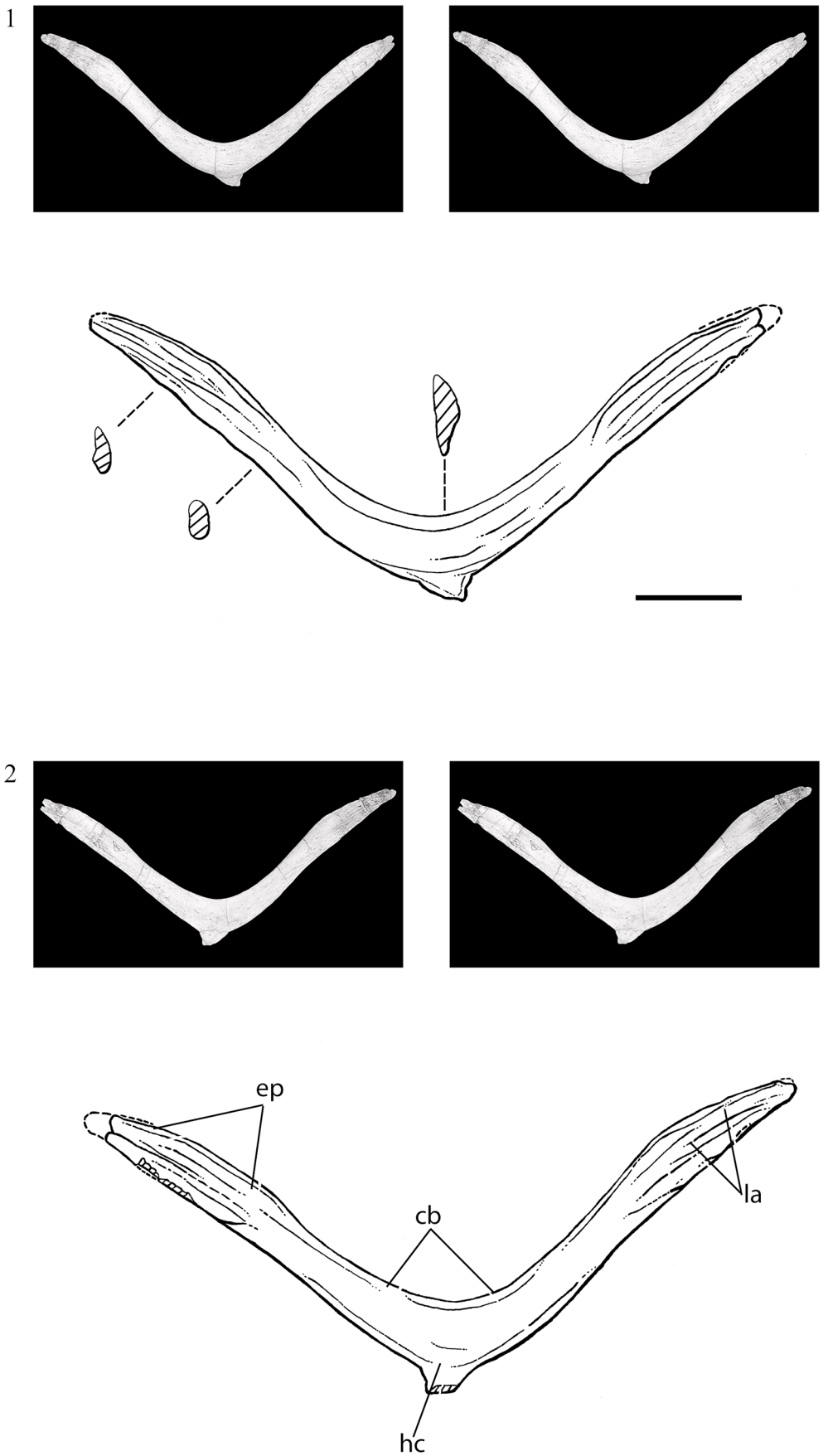


FIGURE *1*—Stereopairs and line drawings of the furcula in *Suchomimus tenerensis* (MNN GAD513). *1*, anterior view and cross-sectional views; *2,* posterior view. Cross-hatching indicates broken bone or a cross-sectional surface. Dashed lines indicate missing portions. Abbreviations: cb, central body; ep, epicleideum; hc, hypocleideum; la, ligament attachment scars. Scale bar equals 10 cm in Stereopairs; 5 cm in line drawings.

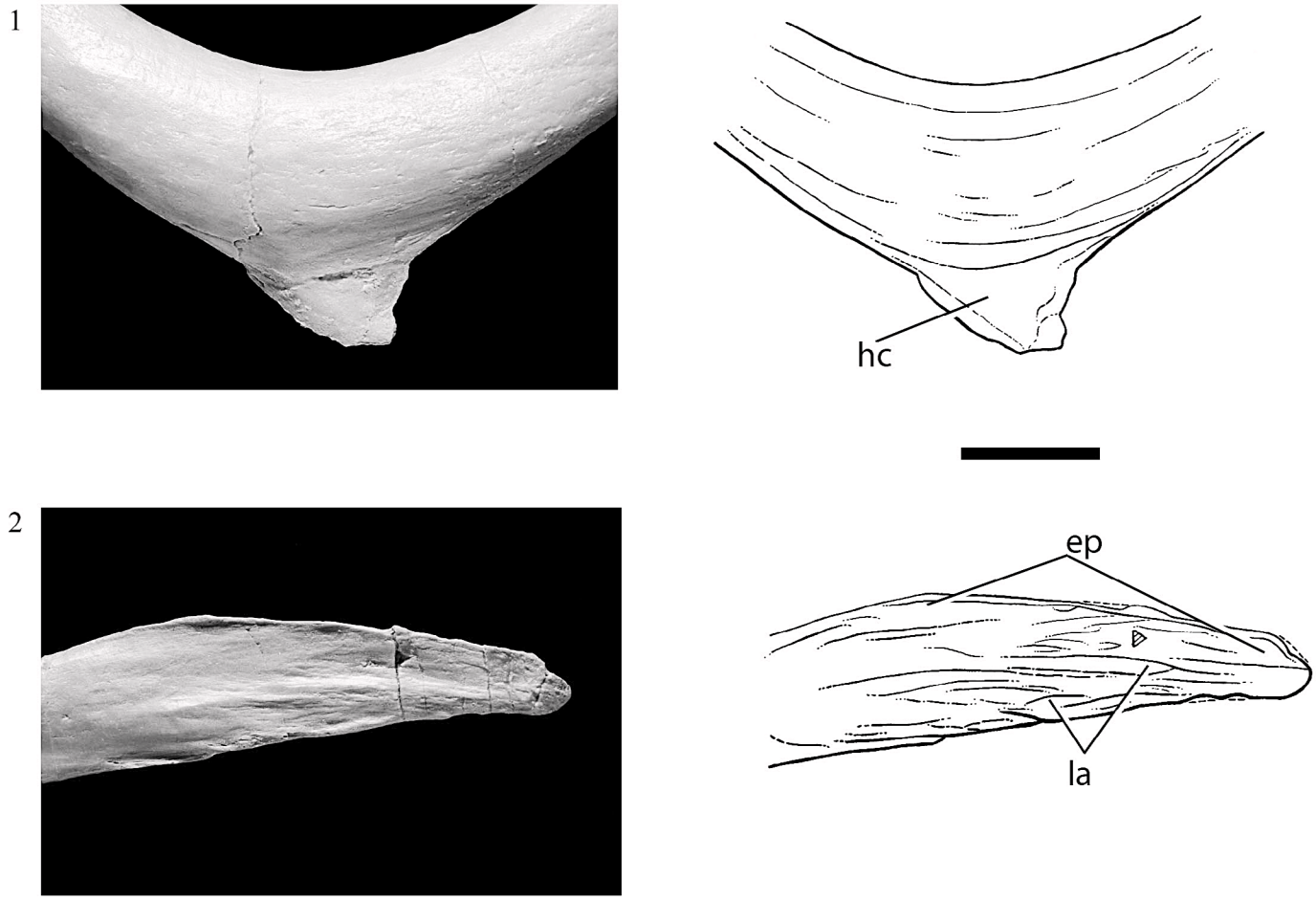


FIGURE 2—Photographs and line drawings of the furcula in *Suchomimus tenerensis* (MNN GAD513). *1*, hypocleideum in anterior view; *2*, epicleideal process in posterior view. Dashed lines indicate missing bone. Abbreviations: ep, epicleideum; hc, hypocleideum; la, ligament attachment scars. Scale bar equals 5 cm.

TABLE 1—Measurements (mm) of the furcula in *Suchomimus tenerensis* (MNN GAD513) and furculae from *Tyrannosaurus rex* (UCRC V1, MOR 980, and MOR 1125). The length of the clavicular process was taken from the more complete right side of each specimen. Parentheses indicate approximation. Abbreviations: NA, not applicable; NE, not exposed.

Measurement	*Suchomimus tenerensis*	*Tyrannosaurus rex*		
		UCRC V1	MOR 980	MOR 1125
Maximum transverse width (between tips of epicleideal processes)	320	(176)	(241)	(288)
Maximum dorsoventral height (from ventral margin of central body to tip of epicleideum)	120	(143)	(182)	(173)
Central body maximum depth (excluding hypocleideum)	29	34	40	40
Central body maximum anteroposterior thickness	9	14	19	17
Clavicular ramus length	180	(114)	(142)	(124)
Clavicular ramus dorsoventral width at mid length	20	24	28	30
Clavicular ramus anteroposterior thickness at mid length	11	17	16	17
Epicleideal process maximum length	70	(31)	(48)	(58)
Epicleideal process maximum width	25	NE	19	25
Epicleideal process maximum width of articular platform	7	NE	10	23
Hypocleideum length	13	NA	NA	NA
Hypocleideum basal width	25	NA	NA	NA
Intrafurcular angle	111°	71°	87°	113°

The fifth furcula known for *T. rex*, comes from a skeleton from northeast Montana (MOR 1125; Fig. 4.5). The specimen is approximately three-fourths the size of the large adult FMNH PR2081 (Horner and Padian, 2004), is approximately 18 years old (Horner and Padian, 2004), and is hypothesized to be a female (Schweitzer et al., 2005). The furcula is broad and U-shaped with an intrafurcular angle of 113° (Table 1). Articular scars are present on the posterior side of the rami. It most clearly resembles the furcula in the tyrannosaurid *Daspletosaurus* (Makovicky and Currie, 1998, figs. 1, 2). However, unlike *Daspletosaurus*, there is no development of a hypocleideum.

CONCLUSION

The V-shaped furcula in *Suchomimus* documents the presence of an ossified furcula in spinosaurid tetanurans. Its broad V-shape and presence of a short hypocleideum constitute the basal condition within Theropoda, and closely matches the form of the furcula in the coelophysids (Downs, 2000; Tykoski et al., 2002), the allosauroid *Allosaurus* (Chure and Madsen, 1996), and the therizinosaurid *Neimongosaurus* (Zhang et al., 2001). The furcula in *Suchomimus* suggests that the anterior portion of the thorax was transversely narrow as has been preserved in *Allosaurus* and suggested for tyrannosaurids (Chure and Madsen, 1996; Makovicky and Currie, 1998).

This paper documents marked intraspecific variation in the furcula of *T. rex* involving its shape and intrafurcular angle. Such variation cautions against the use of subtle changes in furcular shape as character-states in phylogenetic analysis. *Microraptor*

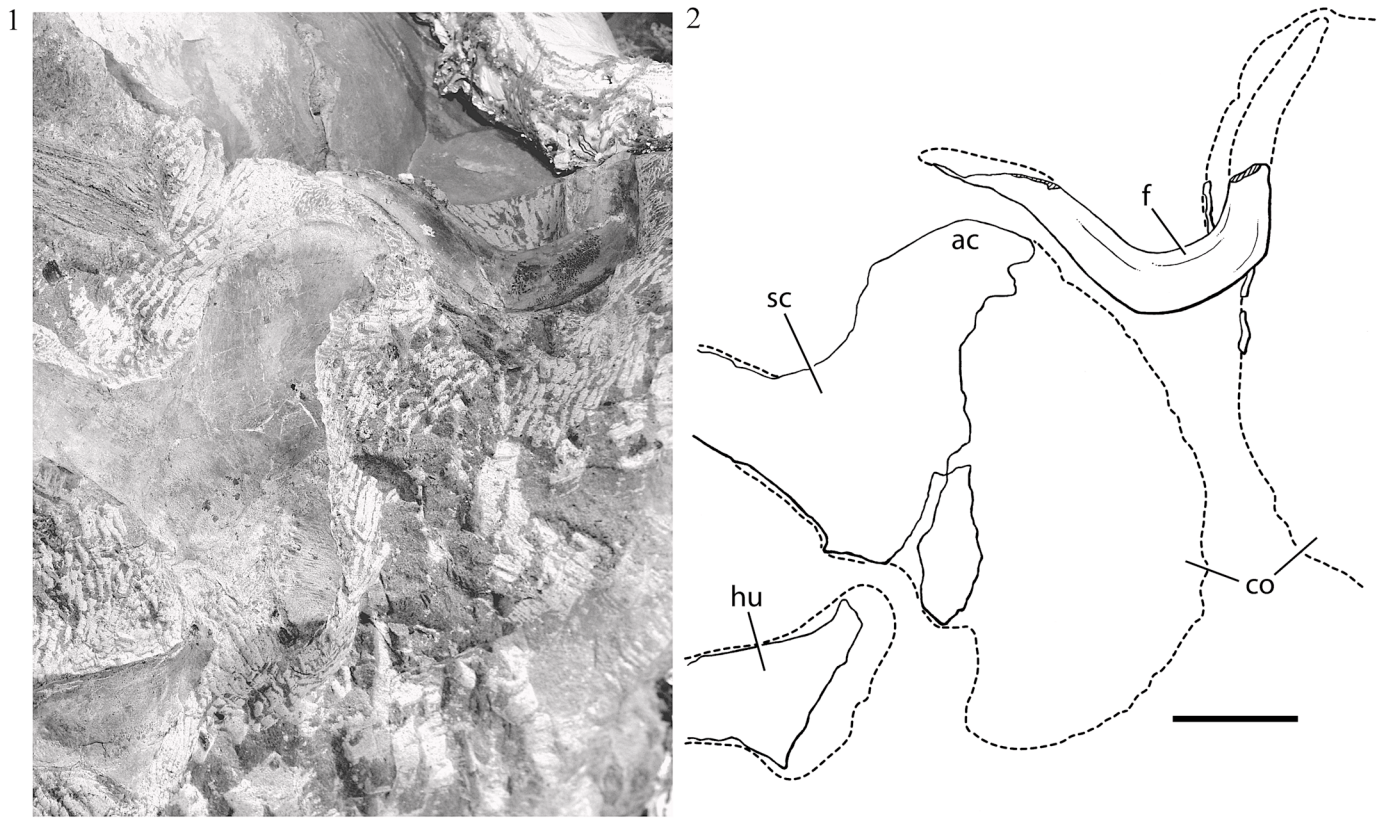
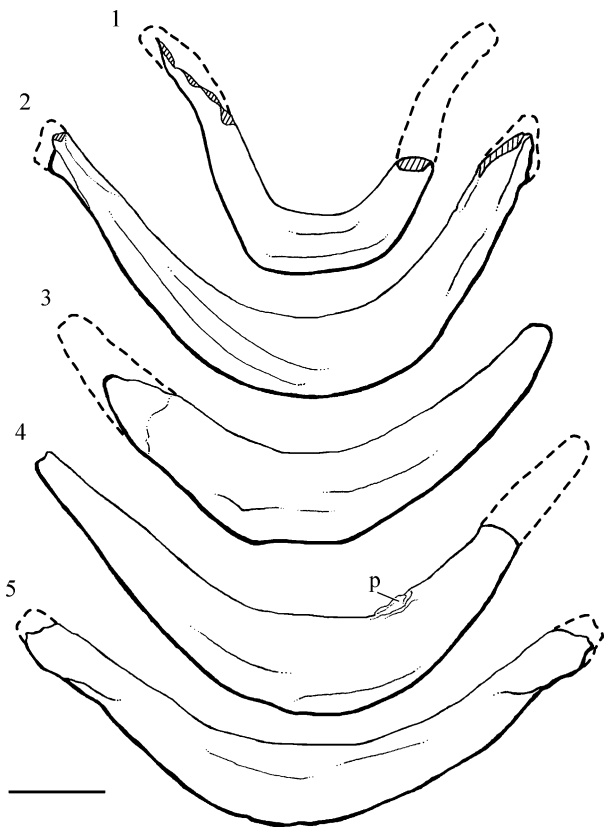


FIGURE 3—Photograph (*1*) and matching line drawing (*2*) of the furcula and pectoral girdle of *Tyrannosaurus rex* (UCRC V1) in anterior view. Cross-hatching indicates broken bone. Dashed lines indicate missing or hidden bone. Abbreviations: ac, acromion; co, coracoid; f, furcula; hu, humerus; sc, scapula. Scale bar equals 5 cm.



zhaoianus and *Gorgosaurus libratus* also show some variation in furcular form, albeit less marked (Hwang et al., 2002). Although variation of the intrafurcular angle in some avians has been correlated with differences in flight function (Hui, 2002), there would seem to be little functional significance to furcular variation in large predators such as *T. rex*. Nor is it possible to attribute shape differences to sexual dimorphism or ontogeny. The skeleton UCRC V1 is at least of subadult maturity as the neural arches are fused or tightly articulated in the anterior dorsal vertebrae and the long bones are approximately two-thirds the length of those of the large adult FMNH PR2081. As one of only a few large-bodied theropod specimens preserved in three-dimensional articulation, UCRC V1 also documents the narrow proportions of the anterior thorax; maximum width of the thorax (distance between acromial processes) is only approximately 30 cm. In closing, basal coeluosaurian theropods such as *Tyrannosaurus* retained a transversely narrow thorax spanned by a furcula with a boomerang, or U-shaped profile. Although this differs from the V-shaped basal tetanuran condition, considerable variation in intraspecific shape may occur.

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FIGURE 4—Line drawing of the morphologic variation in the five *Tyrannosaurus rex* furculae. *1*, UCRC V1; *2*, MOR 980; *3*, FMNH PR 2081; *4*, CMI 2001.90.1; *5*, MOR 1125. Cross-hatching indicates broken bone. Dashed lines indicate missing bone. Abbreviation: p, pit. Scale bar equals 5 cm.

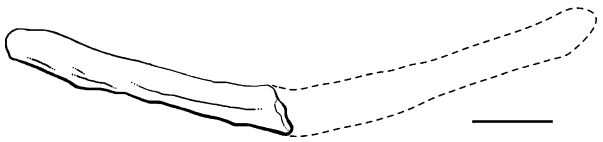

FIGURE 5—Line drawing of the mounted furcula of *Tyrannosaurus rex* (FMNH PR 2081) in anterior view. Dashed lines indicate missing portions. Scale bar equals 5 cm.

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