An Assessment of *Macropus Giganteus* as a Biomechanical Model of the Pediatric Thorax

S. H. Lau[1], K. A. Rafaels[1], C. R. Bass[1], and R. W. Kent[1]
[1]University of Virginia

ABSTRACT

*The interaction between the seat belt and the pediatric thorax is important since this interaction dictates the kinematic trajectory of the head. To better understand this interaction, animal surrogates that are anatomically similar to the human child have been considered for testing with various belt geometries. Primates are anatomically similar to humans in many respects, but they are high on the phylogenetic order, are difficult and not readily available to test, and their stature, mass, and age-size equivalence to humans would require both size and modulus scaling. Other animal surrogates, including porcine subjects, have been studied for thoracic and abdominal response, but their anatomical differences (e.g. lack of a clavicle) do not provide the geometric similitude required to study the complex loading of a seatbelt. This paper presents an anatomically and developmentally based investigation of the eastern grey kangaroo (*macropus giganteus*) and its feasibility as a biomechanical model of the pediatric human's chest. At a height of 116cm (height of 6-year-old human) a kangaroo is 25% of adult sexual maturity, compared to 39% for the human, indicating that organ development and hence modulus may be similar. In contrast, no primate has a size-development relationship so close to the human. At this height, the kangaroo's chest circumference and chest depth are within 8% and 16% of the 6-year-old human. The masses of the liver, heart, lungs, and kidneys of the kangaroo are also similar to the human's at this developmental level. Several anatomical differences between human and kangaroo thoraces were noted, however, including a difference in clavicle length and morphology, the position of the scapula, and the spinal column curvature. These differences are qualitatively less than those associated with other animal models, even primates. Furthermore, the age-size-developmental equivalence between humans and kangaroos avoids some of the difficulties associated with scaling. In the absence of pediatric human cadavers, it is concluded that* macropus *deserves consideration as a biomechanical model for studying the interaction between vehicle restraint systems and the 6-year-old human's chest.*

INTRODUCTION

A model that characterizes the pediatric thorax on a structural level is important to study the interaction between the seat belt and thorax as this interaction dictates the kinematic trajectory of the head. Traumatic brain and skull injuries are the most common serious injuries sustained by children in motor vehicle crashes regardless of age, group, crash direction, or restraint type (Arbogast et al., 2004, Howard et al., 2003). Head injuries are responsible for one-third of all pediatric injury (Adekoya et al., 2002, Thompson and Irby, 2003) and are particularly relevant clinically as the developing brain is difficult to evaluate and to treat.

Previous thoracic research has been performed on adult cadaver subjects through hub impact tests and table top dynamic non-impact tests. Table top dynamic non-impact tests on adult subjects have included various loading conditions: belt, double belt, distributed, and hub (Figure 1, e.g., Backaitis and St-Laurent 1986, Cesari and Bouquet 1990, Kent et al. 2004). Adult cadaver subjects are more readily obtained than pediatric subjects, so minimal research has been performed on pediatric thoracic characterization.

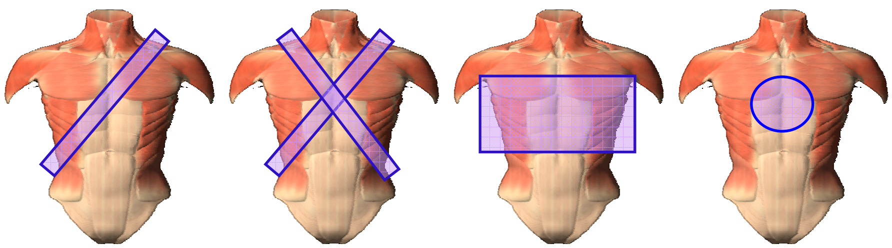

Figure 1: Dynamic non-impact test loading conditions:
(left to right) belt, double belt, distributed, and hub.

Scaling the existing adult corridors to represent children is not straight forward due to the uncertainty associated with any assumptions regarding geometric similitude and modulus scaling. Therefore, an experimental model for validation of the technique is needed. The experimental model should be anatomically similar to a human child to provide an appropriate restraint interaction. It is important to consider age-dependent changes in thoracic properties. If a model having a size-development relationship similar to a human could be identified, then it may be reasonable to apply the data directly to the human without the need for any scaling. It would be particularly advantageous to avoid modulus scaling by choosing a model that is at the appropriate developmental stage when it is the size of a 6-year-old child.

Pediatric PMHS testing is difficult and historically there is very little biomechanical data available. The availability of pediatric cadaver specimens for testing is limited, though recent studies have presented limited findings using this model. Kallieris et al. (1976) comparing child cadavers and child dummies in restraint systems and Ouyang et al. (2006) performed dynamic hub impact tests on pediatric cadaveric subjects to determine the structural response of the thorax, but the lack of post-natal, preadolescent cadaver tissue continues to hamper research on the biomechanical behavior and injury tolerances of children.

Animal models have historically been one widely used method to obtain biomechanical injury information, and may solve the aforementioned problem if an appropriate model of the pediatric human can be found. Animal models from a variety of species have been used to characterize various biomechanical aspects of the thoraco-abdominal region (e.g., Viano and Warner, 1976, Roberts et al., 1966), including a recent study for the human child (Kent et al.

2006). However, we are aware of no studies that have considered the complex loading of an automotive seatbelt, presumably because the anatomical limitations of any of these historical models (e.g., porcine, canine, and ursine), such as the lack clavicles, precludes them from representing the human response, which is strongly influenced by anatomy (Kent et al. 2004). Thus, there is a general need for the development of a new animal model that is both available for biomechanical testing and anatomically similar enough to the human that its behavior in response to belt loading can be assumed to be similar to a human's. For the special case of the human child, the model should have a size-to-development relationship analogous to a human's. The specific goal of this study was to assess one candidate, *macropus giganteus*, relative to several primates. The non-human primates assessed in this study were the chimpanzee (*pan troglodyte*), baboon (*paio hamadryas*), and rhesus monkey (*macaca mulatta*). The taxonomy of the kangaroo (*macropus giganteus*) diverges from that of the human at a higher level (order, see Figure 2, left) than do the non-human primates, but the anatomical similarity of the upper body (Figure 2, right) prompted its consideration along with these closer relatives.

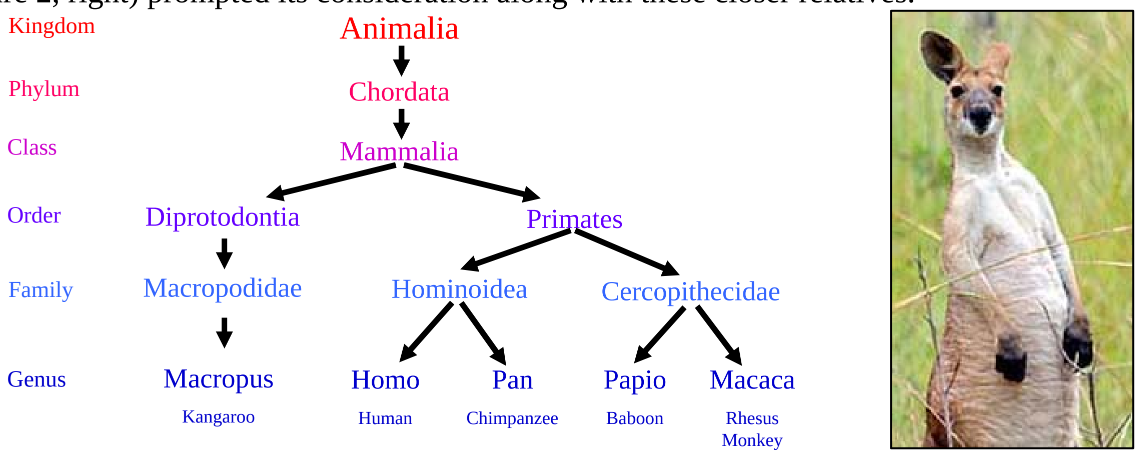

Figure 2: Taxonomy of species assessed during study and a photograph of *macropus*.

METHODS

Growth Development

To analyze size development, the sexual maturity of the various animal models was compared at the stature and mass of a 6-year-old human equivalent. Osseus development was also considered since the formation of ossification centers during pediatric development may influence thoracic response.

Anatomy

Anatomical data was obtained for humans and the animal subjects for this assessment. Stature and mass of the animal subjects were compared to assess the need for scaling. The morphology of the rib cage, scapula, clavicle, sternum, and vertebra were also analyzed, as was the orientation of the scapula on the rib cage. Masses of the thoracic organs (e.g. kidney, liver, heart, lungs) were compared between human and kangaroos. Body mass distribution was calculated from anatomical data for each of the animal subjects.

The University of Adelaide has provided us a CT scan of a mericut red kangaroo (*macropus rufus*) at a resolution of 0.69x0.69x1.60mm which has been instrumental in determining actual anatomical morphologies, which has similar anatomical features to the eastern grey kangaroo (*macropus giganteus*). Additionally, a physical red kangaroo skeleton (age undetermined) was obtained from Skulls Unlimited International, Inc. This will aid in analyzing bone morphology and future comparisons of the various proposed loading conditions.

RESULTS AND DISCUSSION

Growth Development

The average human 6-year-old has a stature of 116cm and a mass of 21kg (Kent et al. 2006). The percent of sexual maturity for the four animals at a stature of 116cm and mass of 21kg are compared relative to a human in Table 1. Skeletal maturity in humans occurs at age 17.25 years for males and 16.25 years for females (Bayley, 1943). It is apparent that the baboon and rhesus monkey in the cercopithecidae family do not represent the human size-development course as well as the other models. The sexual maturity of the chimpanzee and kangaroo correlates relatively closely to human 6-year-old.

Table 1: Sexual maturity when stature of 6-year-old human

	Man	Chimpanzee	Baboon	Rhesus Monkey	Kangaroo
Percent of sexual maturity when at stature of 116cm	39	44	mature	never	25
Percent of sexual maturity when at whole body mass of 21kg	39	37	never	never	44

[Sources: Kent et al. 2006, Shefferly, 2005, Shefferly, 2004, Seinfeld, 2000, Joo, 2004]

Compared to chimpanzees, humans exhibit a longer period of skeletal and dental growth and development (Mulhern and Ubelaker, 2003). Baboon bone relative to dogs, cows, and rabbits is more similar to human bone regarding fracture, microstructural and compositional properties, and their skeletal remodeling process parallels that of humans. No literature was found describing the osseous development of kangaroos, or the structural development of long bones in any of the study animals. Bone mineral density has, however, been published for the primates during development (Table 2).

Table 2: Bone Mineral Density (BMD in g/cm^2)

Human Equivalent Ages	Man	Chimpanzee	Baboon	Rhesus Monkey	Kangaroo
2.8 years old	0.48	0.43	1.01	0.267	NA
6 years old	0.67	0.48	1.02	0.38	NA
9.6 years old	0.735	0.7	1.05	0.47	NA
16 years old	1.15	0.83	1.11	0.727	NA
Adult	1.58	1.17	1.6	0.85	NA

[Sources: Cerroni et al., 2000, Del Rio et al. 1994, Hamada and Udono, 2002, Hamada et al. 2003, Havill et al., 2003, Havill, 2004, Wang et al., 1998]

Anatomy

Individual Structures. The morphology of individual structures in the thorax is important for the belt interaction during testing. A comparison of rib cage and scapula morphology is provided in Figure 7 and Figure 8 in the Appendix, and rib cage and scapula orientations are illustrated in Figure 9. The human and chimpanzee rib cages are more elliptical along the frontal plane with scapulae dorsally situated, whereas the baboon and rhesus monkey rib cages are narrower and longer along the sagittal plane with the scapula situated laterally (Chan, 2007). The kangaroo rib cage is more circular than elliptical along the frontal plane compared to the human with the scapulae also located lateral to the rib cage. One noticeable difference in scapula morphology is the width and quadrilateral shape of the kangaroo scapula compared to the human's scapula.

An important anatomical feature for modeling belt interaction with the thorax is the clavicle, which most quadrupedal animals (e.g., bears, dogs, and pigs) lack. Aside from primates, some waning species have well-developed clavicles, such as the duckbill platypus, kangaroo, opossum and armadillo (Codman, 2008). Figure 10 in the Appendix depicts clavicles of the model subjects. The kangaroo clavicles are relatively short compared with humans, however, kangaroos have highly developed shoulders at an early age due to the need to "swim" into the pouch to reach its mothers tits (Dawson, 1995).

The human sternum is comprised of three bones, the manubrium, gladiolus and xiphoid process. The sternum of the other animal subjects has 6-8 bones in the sternum including a manubrium and xiphoid process (Figure 11 in Appendix). In humans, the first seven pairs of ribs articulate with the cartilage with three false ribs attached to the cartilaginous portion of the next above rib, and two floating ribs that are not attached to the sternum. The chimpanzee sternum consists of six bones, with the articulation of ribs the same as humans except there is an additional 13^{th} floating rib. The baboon and rhesus monkey sternums have eight bones with the first eight pairs of ribs articulating with the surface. The baboon has three false ribs, and only one floating rib, whereas the rhesus monkey has two false ribs and two floating ribs (Swindler, 1973, Szebenyi, 1969). The kangaroo sternum has six bones with the first seven pairs of ribs articulating with cartilage, three false ribs, and three floating ribs. The sternum-rib articulation of the human and kangaroo are the same with the exception of an additional floating rib in the kangaroo, and three additional sternal bones which might result in more flexibility.

The vertebral bodies of the studied animals (Figure 12) are not different enough to be a major consideration in our study. Humans have an upright posture requiring the "S" shaped curvature while the kangaroo, rhesus monkey and baboon have a semi-erect posture that the "C" shaped spinal column supports, and they have tails to help with balance. The spinal column of the chimpanzee is straighter to accommodate its posture since it does not have a tail. Differences in the curvature of the spine among the animals (Figure 13) are not critical since fixed-spinal tests will be performed. Overall, anatomical structures of *pan*, *papio*, *macaca*, and *macropus* are reasonably comparable in terms of their use as a biomechanical model of the chest.

Stature and Mass Comparison. The kangaroo was the only animal considered that had comparable stature and mass to that of a human (Figure 3). The eastern grey kangaroo species was chosen for assessment due to its comparable mass and stature (3.5-90 kg. and 1.5-1.8m. tall) (Joo and Myers, 2004) compared to the smaller species in the *macropus* genus, red kangaroos (90kg. and 650-1200mm tall) (Dewey and Yue, 2001) and western grey kangaroos (28.25kg. and average 1585.50mm. tall) (Miller, 2002).

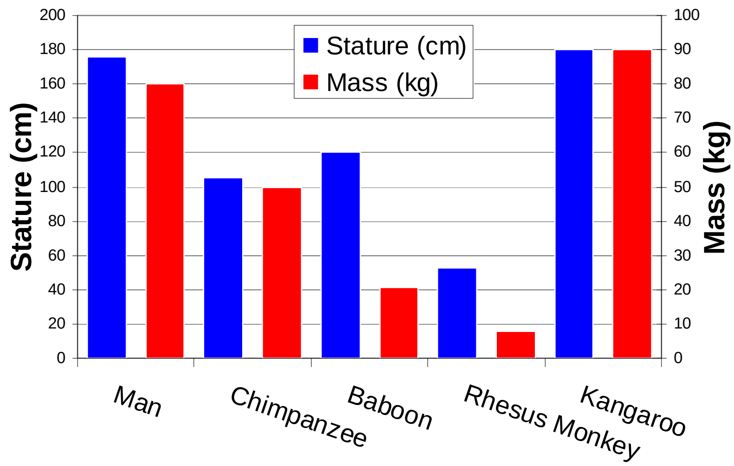

Figure 3: Adult stature and mass.
[Sources: Kent et al. 2006, Shefferly, 2005, Shefferly, 2004, Seinfeld, 2000, Joo, 2004]

Despite differences in the kangaroo rib cage compared to the human rib cage, overall dimensions of the thorax are similar at both the pediatric (6-year-old equivalent development) and adult stages. The chest circumference, chest depth, and thoracic vertebral length of a 6-year-old and adult human were compared to their kangaroo human equivalence in Figure 4. Humans have a larger chest circumference because they are more elliptical in the frontal plane. Kangaroos have a greater thoracic vertebral length compared to humans. Overall the chest dimensions comparing human and kangaroo subjects are similar.

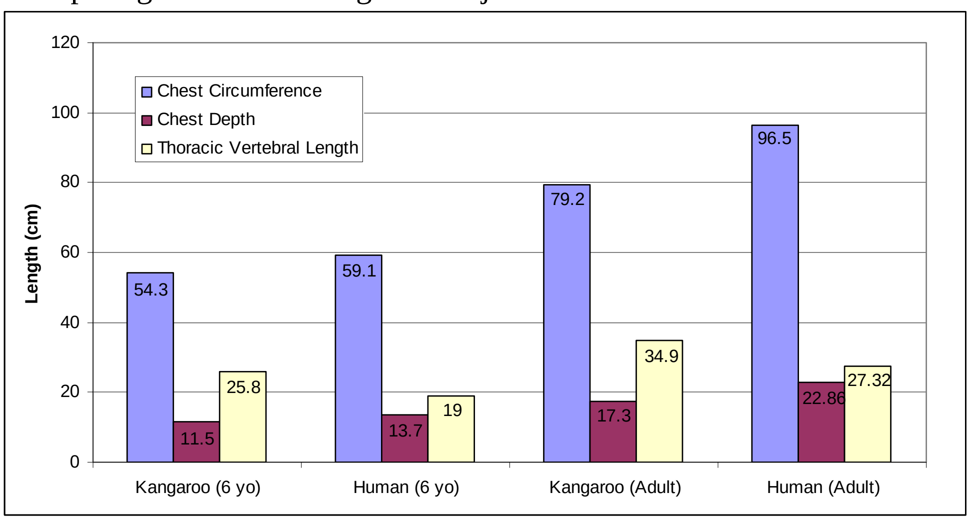

Figure 4: Thoracic measurements (kangaroo age is human developmental equivalent).
[Sources: Hopwood, 1976, Snyder 1977]

Organ Masses. Size, shape, and location of the internal thoracic organs are important to consider when studying belt loading. A mass comparison of the liver, heart, lungs and kidneys of kangaroos and humans at age 6-years-old (equivalent) and adult is shown in Figure 5. All of the organ masses are similar with the human liver being larger than the kangaroo and the kangaroo heart slightly larger than the human heart. Kangaroos are posturally semi-erect animals so it can be inferred that the organ arrangement is similar to that of humans.

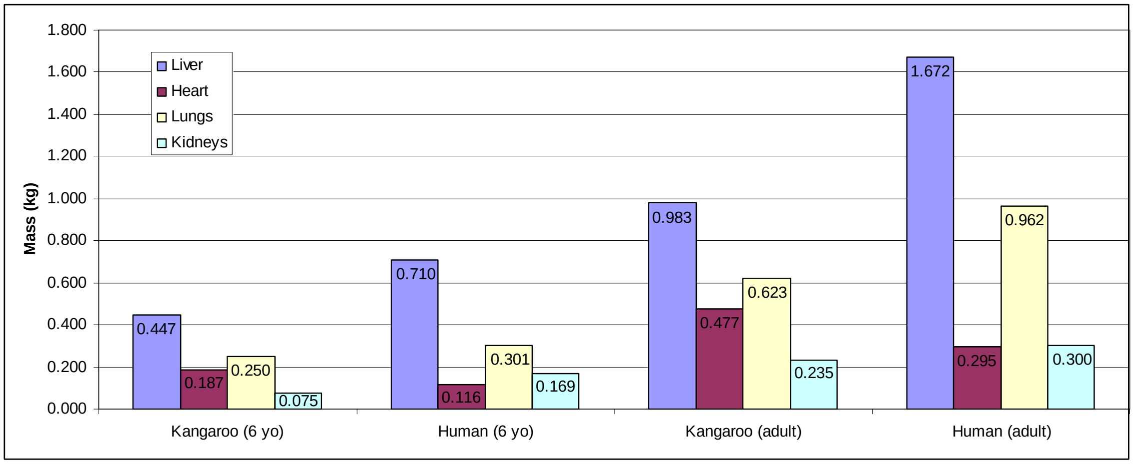

Figure 5: Organ mass comparison.
[Sources: Tribe and Peel 1963, Kent et al. 2004]

Body Mass Distribution. The body mass distribution of adult subjects was considered as an overall description of whole body shape. Table 3 shows the distribution of body segments compared to the adult human. There were no available data found on baboons and limited applicable data on grey kangaroo subjects to determine body mass distribution. Also, the only available data found for a comparative analysis of body mass distribution of a 6-year-old human equivalent were for the rhesus monkey, provided in Table 4 in the appendix. Minimal information was inferred from the body mass distribution comparision.

Table 3: Body Mass Distribution-Adult

Percent of Total Body Weight	Man	Chimpanzee	Baboon	Rhesus Monkey	Kangaroo
Total Upper Limbs	9.88	18.92	NA	13.88	NA
Total Lower Limbs	39.72	25.36	NA	22.89*	NA
Head and Trunk	50.4	55.73	NA	63.15	NA
Forearm and Hand	2.23	4.97	NA	3.11	0.56
Shank and Foot	5.7	5.06	NA	4.51	11.3*

* Tail included [Sources: Bourne, 1975, Hopwood, 1976, Poole et al. 1982, Tribe and Peel, 1963, Snyder et al., 1977]

CONCLUSIONS

The *macropus giganteus* appears to be a promising biomechanical model for studying the interaction between vehicle restraint systems and the thorax, particularly for children since the stature and body mass of a kangaroo when it is at the sexual developmental level of a 6-year-old child are similar to those of a 6-year-old child. Sexual development is, of course, an incomplete descriptor of factors such as osseus development and the modulus of soft tissues, but there are virtually no studies documenting *macropus* development at the desired level of detail. The kangaroo as a developmental analog to the human may prove particularly beneficial as a biomechanical model since it may preclude the need for modulus and even size scaling of the response data, and may facilitate the direct application of response data to the development and benchmarking of human child models.

ACKNOWLEDGEMENTS

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AUTHOR LIST

1. Sabrina H. Lau
    1011 Linden Avenue
    Charlottesville, VA 22902
    434-296-7288 ext 120
    SLau@virginia.edu

2. Karin A. Rafaels
    1011 Linden Avenue
    Charlottesville, VA 22902
    434-296-7288 ext 122
    Kar3k@virginia.edu

3. Cameron R. Bass
    1011 Linden Avenue
    Charlottesville, VA 22902
    434-296-7288 ext 118
    crb7q@virginia.edu

4. Richard W. Kent
    1011 Linden Avenue
    Charlottesville, VA 22902
    434-296-7288 ext 133
    Rwk3c@virginia.edu

APPENDIX

Table 4: Body Mass Distribution-6-year-old

Percent of Total Body Weight	Man	Chimpanzee	Baboon	Rhesus Monkey	Kangaroo
Total Upper Limbs	9	NA	NA	13.52	NA
Total Lower Limbs	30	NA	NA	26.28	NA
Head and Trunk	61.2	NA	NA	61.04*	NA

* Tail Included [Sources: Snyder 1977, Grand 1977]

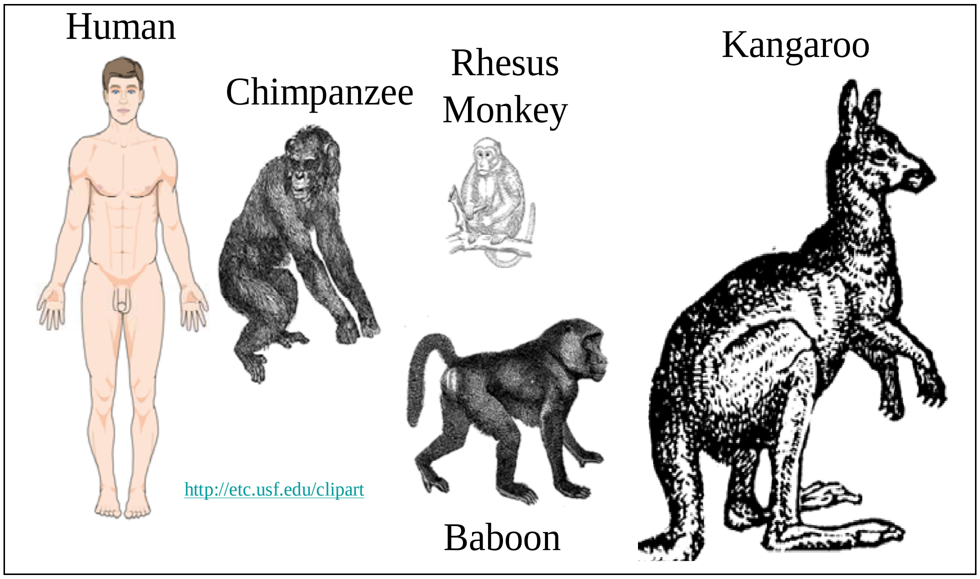

Figure 6: Relative sizes of adults of selected species.

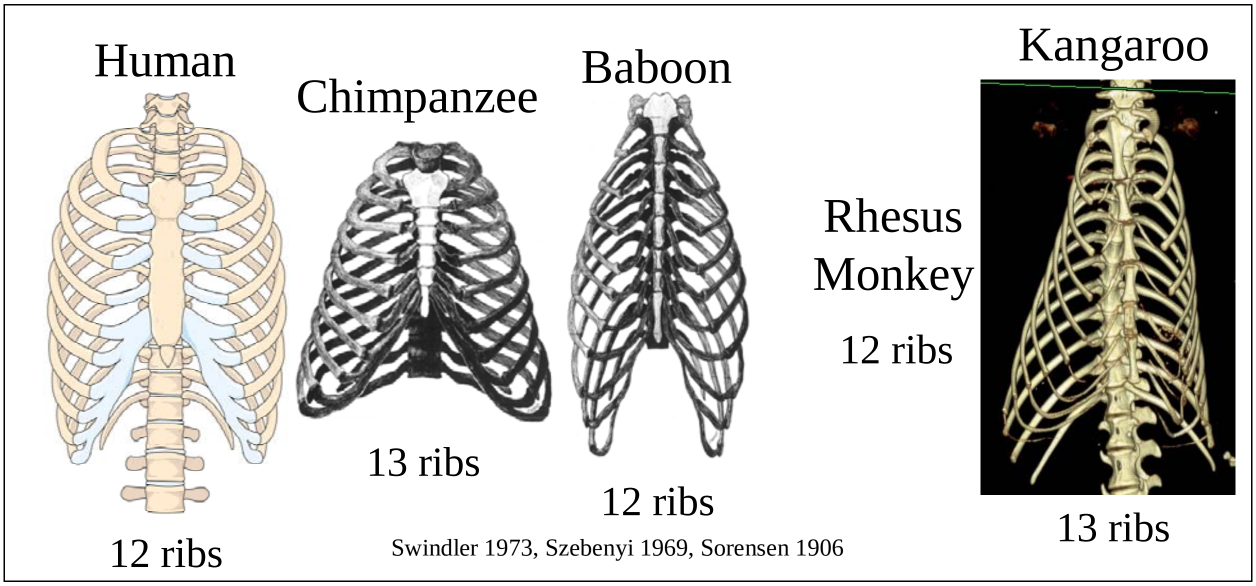

Figure 7: Rib cages of animals considered in this study.

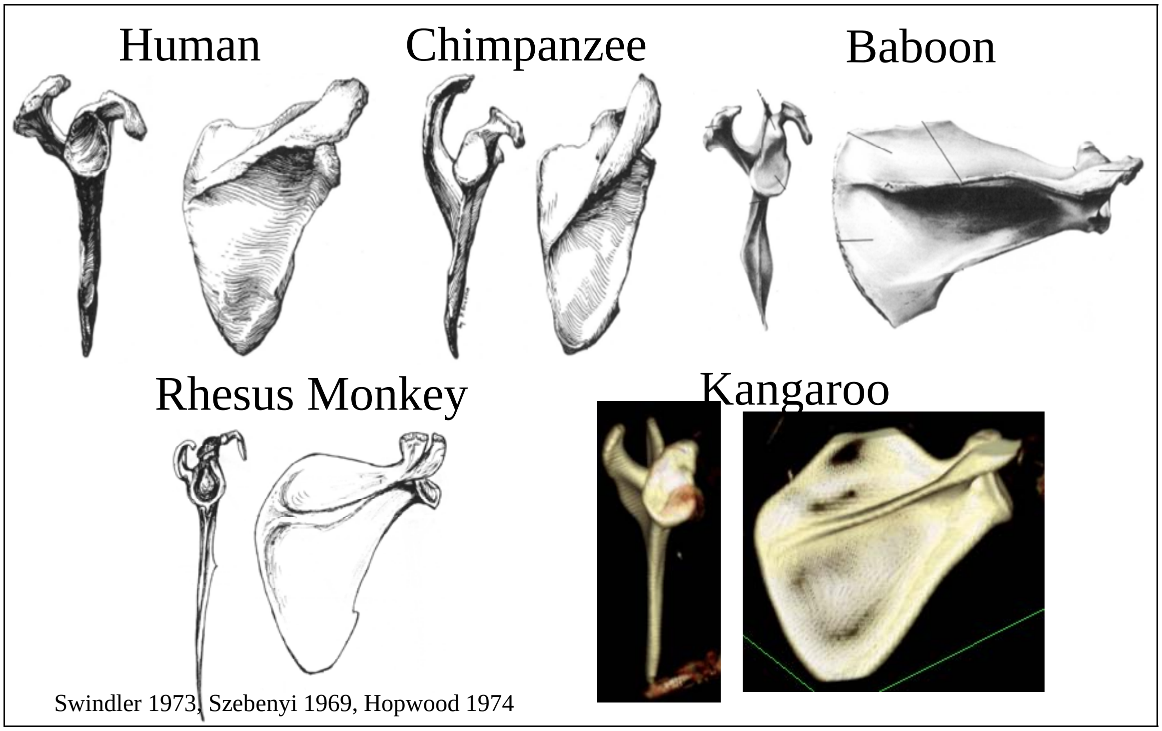

Figure 8: Scapula of animals considered in this study.

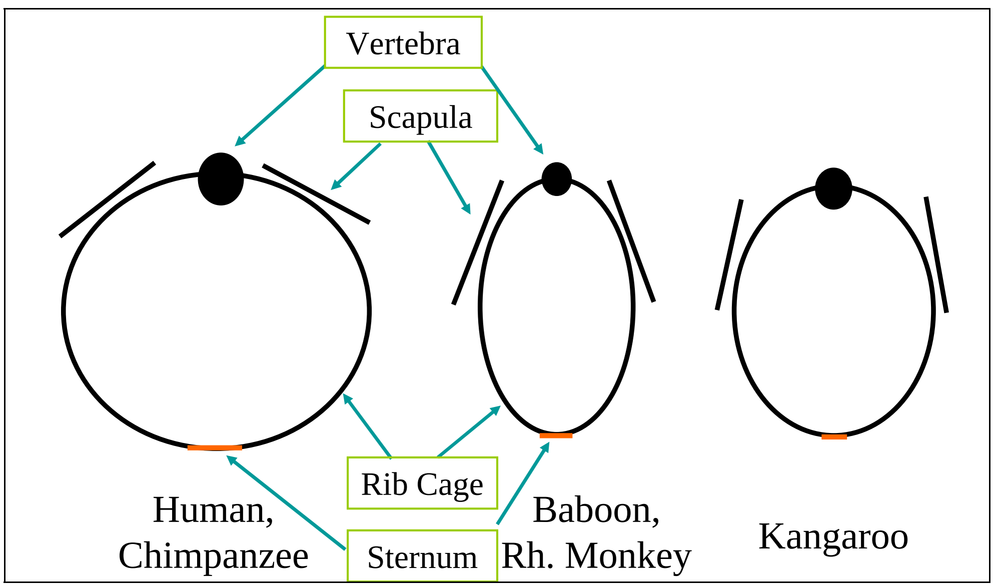

Figure 9: Schematic depictions of rib cage and scapula orientations.

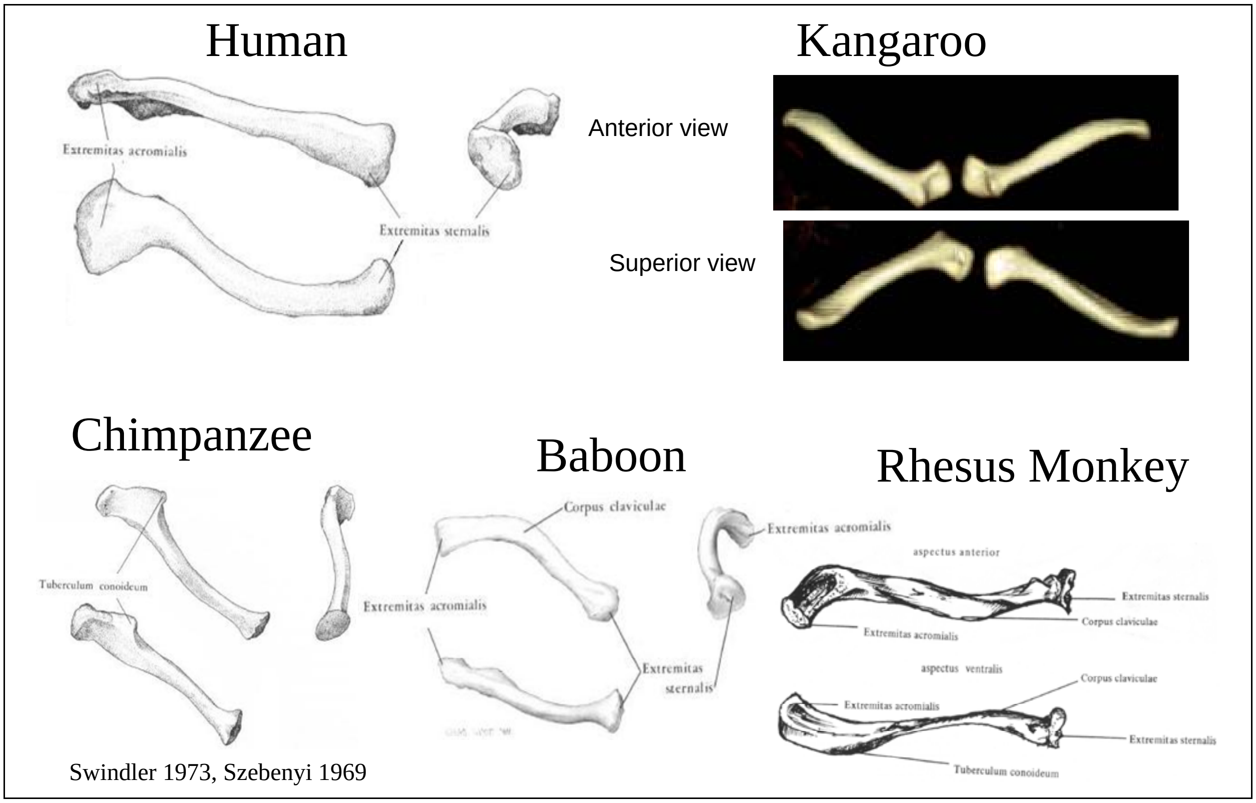

Figure 10: Clavicles of animals considered in this study.

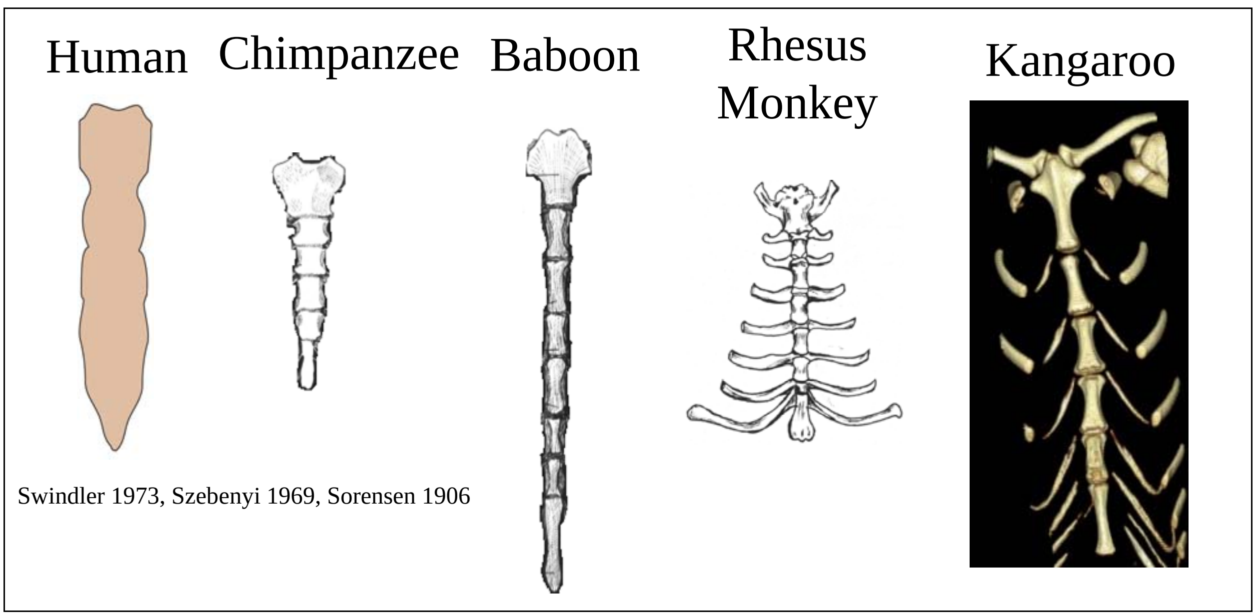

Figure 11: Sterni of animals considered in this study.

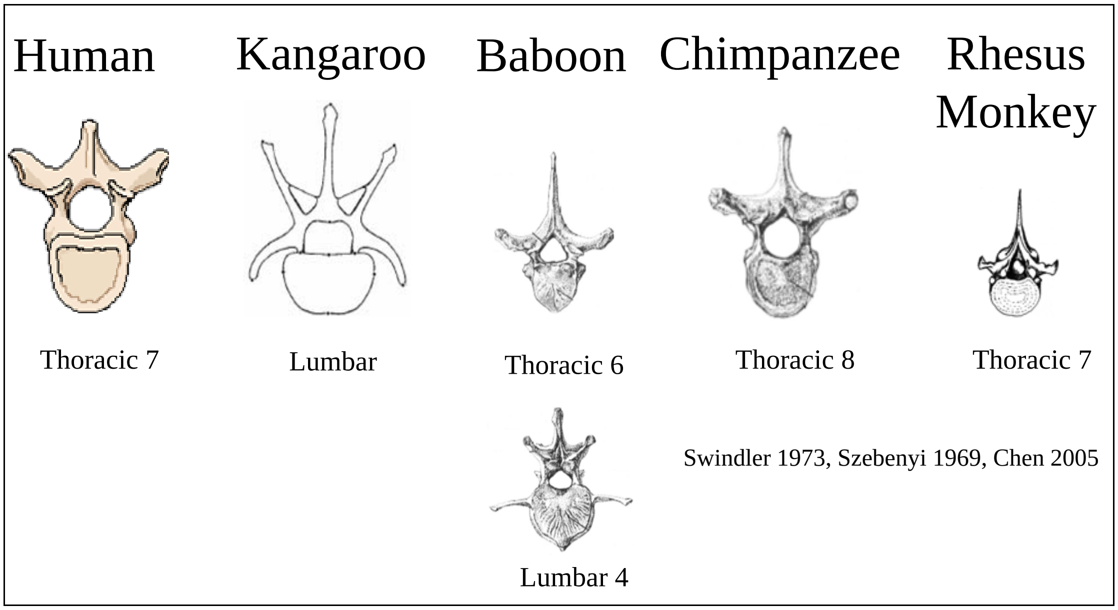

Figure 12: Vertebrae of animals considered in this study.

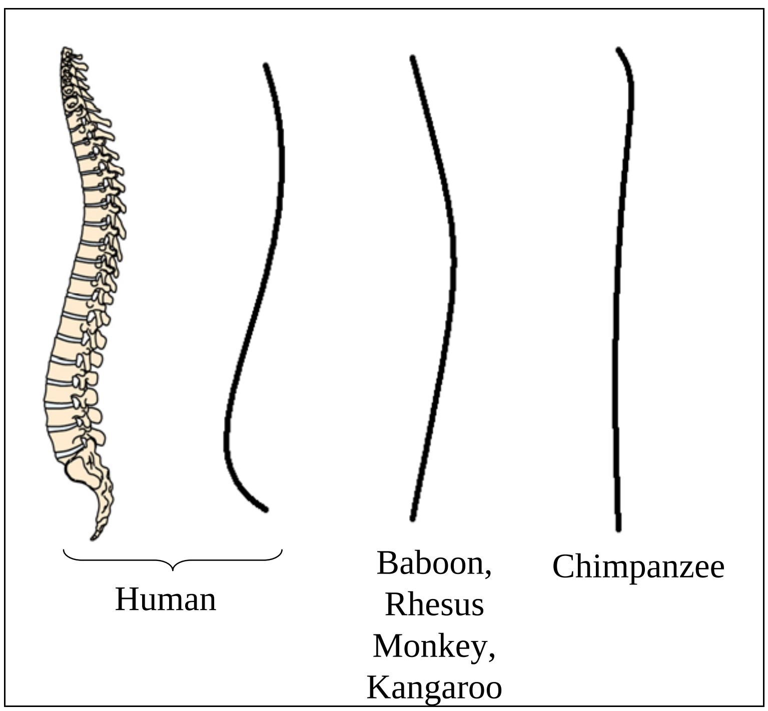

Figure 13: Spinal column curvature.