In Vivo Analysis of Canine Intervertebral and Facet Motion

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Using an instrumented spatial linkage, a method for measuring intervertebral motion *in vivo* was developed and used on six dogs. The segmental motion was recorded as the animals were exercised in routine functions. The standing posture was found to be a repeatable position. During walking, the average excursion between opposing facets was 3.4 ± 1.3 mm, as the L2–L3 motion segment moved into 2.3° of kyphosis with respect to the standing position. This method has the ability of measuring facet motion (± 0.7 mm), vertebral body motion (± 0.5 mm), and vertebral body rotations (± 0.6°) with suitable accuracy such that it is a useful tool in documenting the *in vivo* response of a motion segment to surgical procedures. [Key words: facet joint, joint mechanics, *in vivo* motion, canine, locomotion]

The spine is a chain of interconnected bony elements, designed to provide structural integrity to the trunk and limited motion for normal function. Motion necessarily occurs at each segment, dictated by the mechanical properties of the intervertebral disc, facet joints, and connecting soft tissue. Abnormalities in this motion are thought to be associated with disc and facet degeneration and neural impingement.[8,10] Whether abnormal loading causes the altered motion and ultimate degeneration or is a consequence of the articular degeneration is unknown. As part of a study of the effects of abnormal motion and loads at the facet joints, the authors have measured the intervertebral motion and motion at the facet surfaces in functioning animals. In this report, we describe a method used to measure *in vivo* motion of the spine during various normal activities of the canine.

Many different techniques have been employed to measure the complete 6-*df* motion between vertebral segments *in vitro*. These methods include using linear variable differential transformers, dial indicators,[21,27]

and instrumented spatial linkages.[22,26] Investigators have inferred motion by measuring the stiffness of spinal segments *in vitro* in fresh specimens.[21,26,27] It is assumed this is a reflection of the *in vivo* motion, but this has not been confirmed by direct measurement.

The conventional method to estimate spine motion in humans is single radiographs at various static positions.[31] Others have attempted to measure three-dimensional *in vivo* spine motion.[4,7,9,23,28,29] Biplanar radiography was one method used, but involves radiation exposure.[3,23,28,29] Dynamic motion measuring methods in humans, using skin-mounted markers, are too insensitive (±0.4 cm accuracy) for measuring spine motion.[4,7] Gregerson et al.[9] measured axial rotation in humans *in vivo* during walking, Lumsden and Morris[18] measured axial rotation at the lumbosacral joint, and more recently Kaigle et al.[11] used a device to measure two-dimensional sagittal plane motion of the lumbar spine. *In vivo* measurement of joint motion has been accomplished in other joints, both in humans and in animals.[13,14,25] Kinzel et al.[13,14] used a 6-*df* electrogoniometer, or instrumented spatial linkage (ISL) to measure shoulder motion during function. We have adapted Kinzel's ISL technique to measure spine motion in the dog.

Success of this method allows addressing several questions related to spine injury and disease. Disc and facet motion could be documented, to establish the interrelationship between facet arthritis and mechanical abnormalities of the disc. The effect of fusion, facetectomy, discectomy, and other surgical procedures on the mechanics of the spinal segment and adjacent segments could be studied.

■ Materials and Methods

The method developed consists of an ISL mounted on stiff pins threaded into the bodies of adjacent vertebrae. This was a two-stage experiment with the pins implanted operatively, and after recovery from the first procedure, extension pins (for ISL mounting) were attached in a much shorter procedure. Approval for the two-stage experiment was obtained from the Research Animal Resources Department before beginning the study. Adult mongrel dogs weighing between 25 and 30 kg were anesthetized with intravenous sodium thiamylal (Surital, Parke-Davis, Morris Plains, NJ) (15 mg/kg) and succinylcholine
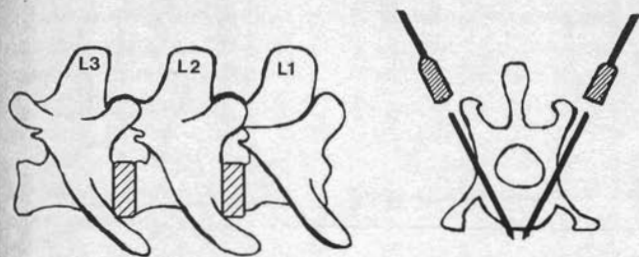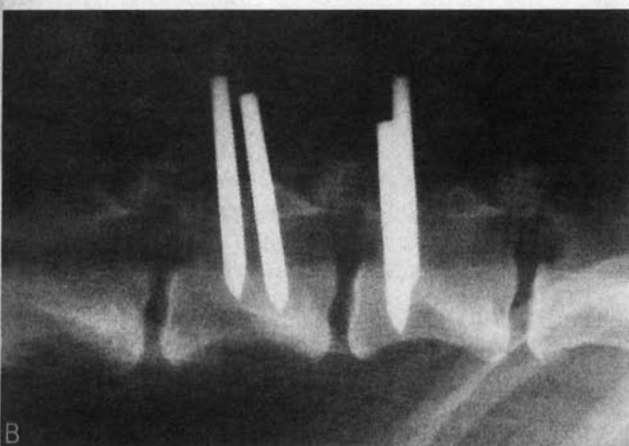
Figure 1. Vertebral bodies L1–L2–L3 with 4-mm Steinmann pins inserted transpedicularly. **A,** Drawing of vertebral bodies and axial view showing how implantable pins were inserted into the bodies. **B,** Radiograph illustrating vertebral bodies L2 and L3 with the Steinmann pins inserted.

Figure 2. Steinmann pin assembly with a 3.8-cm implantable portion (s), a 2-cm threaded collar (c), and the 11-cm extension (e).

(0.5 mg/kg), and maintained with halothane inhalation anesthetic. Crystalline penicillin was added to the intravenous fluids. Four 4-mm threaded stainless steel pins, 3.8 cm in length, were placed transpedicularly and bilaterally, into L2 and L3 through two paralumbar incisions. Of each pin, 1.8 cm was threaded into bone, and 2.0 cm protruded into the paralumbar musculature (Figure 1). The incisions were closed primarily in three layers, and the dogs received Nubain (Du Pont, Wilmington, DE) for postsurgical pain. Pin placement was verified radiographically.

Seven days later, the dogs were given atropine subcutaneously and Surital (5 mg/kg) intravenously to induce a brief general anesthesia. The original incisions were reopened, and complimentary 11-cm pins with threaded sleeves 2 cm in length were firmly attached to each implanted pin (Figure 2). Lightweight aluminum cross-bars were attached to each set of pins to enhance structural rigidity. A long-acting local anesthetic (bupivacaine 1%) was injected all about the incision, and the skin was loosely approximated about the protruding pins, so as not to impede pin movement. Once the animals had completely recovered from the anesthetic, an ISL was mounted on the pins. This was a spatial linkage system constructed with six potentiometers to measure the 6 df between two rigid bodies.[26] The analog signals from the potentiometers were fed into an analog-to-digital converter (Metrabyte Das 16) and a computerized dat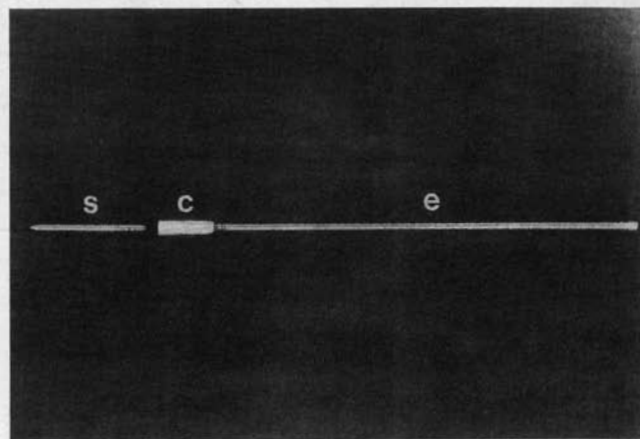a acquisition system (custom driven by an Asyst software package) was used to collect and process the data. Data were collected at 20 samples per second for 5 seconds.

Each dog was put through a series of maneuvers, including standing, walking, moving from sitting to walking, turning, and moving from a four-leg stance to a hind leg position. The turning maneuver was a voluntary motion on the part of the dog as food was used to coax the animal into a right- or left-turn posture. Each of these maneuvers were repeated eight times. Instrumented spatial linkage voltage data were collected throughout 5 seconds of each maneuver. When testing was complete, the dogs were given acepromazine followed by a euthanasia solution of "T61" (embutramide, mebezonium iodide, and tetracaine hydrochloride; Hoechst Pharmaceuticals). Six animals were tested in this manner.

After testing, the spines were harvested and debrided of unnecessary soft tissue, preserving the disc, ligaments, and joint capsules. The motion segment, with the pins and ISL still in place, was potted at each end in dental plaster to fit a loading device. To provide local coordinate systems, the transverse and spinous processes of each vertebral body were digitized, using a three-dimensional digitizer.[26] The geometry of the canine vertebral body was such that the centroid of the points digitized defined an origin near the posterior longitudinal ligament, as shown in Figure 3. The orthogonal cartesian coordinate system also was obtained from these three points. In addition, points on opposing surfaces of the right articular facet joint were digitized. Once the bony and ISL coordinate systems were defined, the transformations between them were determined. The details of the analytical methodology are given in reference 26. These transformation matrices were constant because the end of the ISL was rigidly attached to each bone by the embedded Steinmann pins. Finally, the ISL was removed and calibrated, by putting it through a series of known positions with voltage data being collected. An optimization program was run to obtain optimum linkage parameters that would minimize the errors in the data collected.[15,16] Data were reduced to vertebral body and facet motion in the coordinate system of L2 relative to L3. Facet motion was determined by computing the position of the inferior articular process of the L2 facet in the local coordinate system of L3 based on the transformation matrices (between L2 and L3) given by the ISL. A computer animation program was developed to assist in
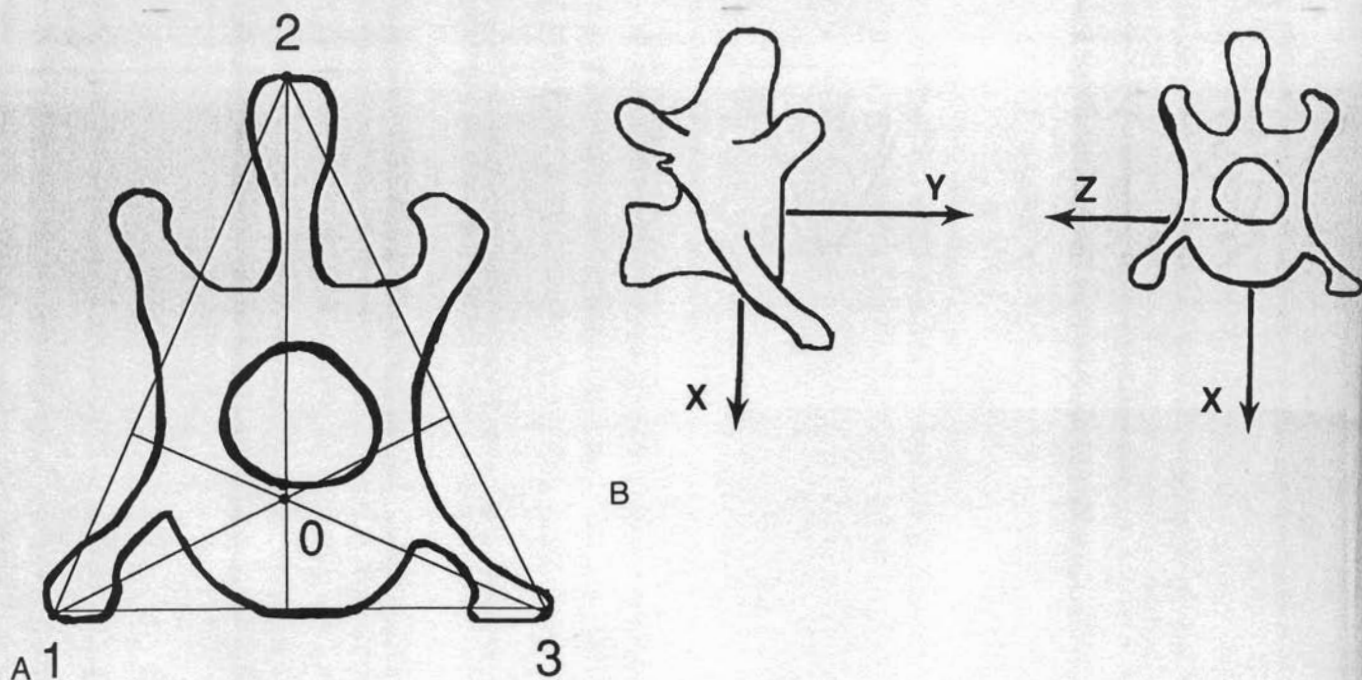
Figure 3. **A**, Axial view of canine vertebral body with digitized points labeled 1 and 3 on the transverse processes and point 2 on the spinous process. The centroid of these points was taken as the origin for the vertebral body local coordinate systems and is labeled 0. **B**, A schematic illustration shows the orientation of the local coordinate systems defined for each vertebral body.

visualizing the facet motion during each of the *in vivo* maneuvers. This animation program was used to create facet motion traces. The relative motion of two points on opposing articular surfaces gave trajectories that were elliptical in form during a gait cycle. To obtain a measurement of the facet motion, the length of the ellipse was measured for each gait cycle of each animal, as shown in Figure 4.

To evaluate the ISL accuracy, separate from data collection, two tests were performed: one, the ISL was mounted on a linear slide (Velmex 2051; accuracy, ± 0.01 mm), and ISL data were collected at 1-mm intervals of the linear slide position. The ISL was calibrated over the same range used with *in vivo* testing. Measurement of the motion of the facet joint was the primary goal of this study; consequently a second test determining the accuracy of the measured distance between a point on a fixed bone and a point on the mobile bone was necessary. An *in vitro* canine motion segment (L2–L3) was mounted in a fixture such that L3 was fixed and L2 was mobile. Threaded Kirschner wires
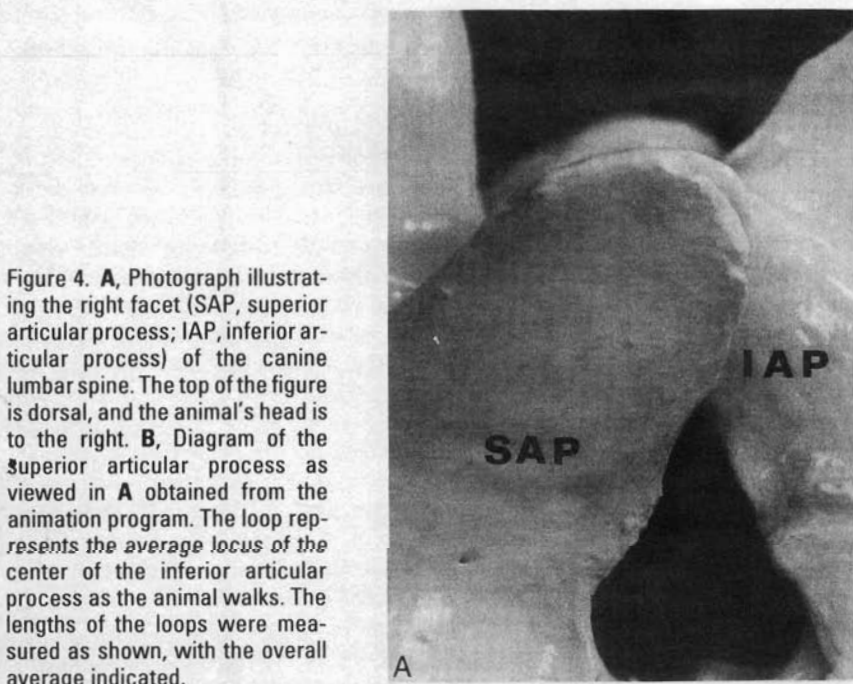
Figure 4. **A**, Photograph illustrating the right facet (SAP, superior articular process; IAP, inferior articular process) of the canine lumbar spine. The top of the figure is dorsal, and the animal's head is to the right. **B**, Diagram of the superior articular process as viewed in **A** obtained from the animation program. The loop represents the average locus of the center of the inferior articular process as the animal walks. The lengths of the loops were measured as shown, with the overall average indicated.

(1.1 mm diameter) were inserted near the mammillary process of the superior articular process of L3 and in the inferior articular process of L2 at approximately the same level. These wires were cut with approximately 4 mm protruding from the bone surface and were 3.5 mm apart. Steinmann pins were inserted in the pedicles, and the ISL was mounted on the pins in an identical fashion as during *in vivo* testing. Distance measurements were made (using a vernier caliper; accuracy, ±0.025 mm) between the ends of the wires protruding from each facet articular process. The distance between the wires was measured with the specimen in a neutral position, extended position, and a flexed position. At each position, the ISL voltage data were collected. The distance between the wires was determined from the ISL data and transformation matrices; an error was determined between the ISL-predicted wire distance and the actual distance measured with the caliper.

■ **Results**

Calibration showed vertebral body accuracy of 0.3 to 0.5 mm when measuring position, and 0.4 to 0.6° when measuring rotation. The results of the ISL accuracy test on the linear slide showed an average position error of 0.04 ± 0.17 mm over a range of 10 mm. The average error between measured and calculated distances when using the ISL to measure distances between points on different bones at the facets was 0.7 ± 0.3 mm.

One animal was killed before testing because of neurologic deficits secondary to a pin insertion that compromised the canal space. The remaining five dogs recovered from anesthesia well, and tested without complications. There were no infections, wound problems, or pin loosening. All pins were placed accurately into the bodies of L2 and L3.

Only the standing, walking, and sit to walking produced consistent data for the animals. The standing posture was found to be a repeatable static position for the animals. The average position orientation (of the L2 with respect to the L3 vertebral body coordinate system) while in a standing posture, over all animals, was repeatable to ±0.5 mm, ±0.8 mm, and ±0.5 mm in the x, y, and z positions, respectively. During standing, the angular orientation of L2 with respect to L3 was repeatable within ±0.7°, ±0.3°, and ±0.7° in the x, y, and z axis rotations, respectively. A significant difference ($P < 0.05$) in the vertebral body orientation and the facet position was found between the neutral standing posture and the average walking posture such that during walking the average angle of the motion segment in the sagittal plane was increased in kyphosis by 2.3°. Another prominent component of vertebral body motion during a gait cycle was a rotation in the sagittal plane of 1.5°, which caused the posterior portion of the vertebral bodies to separate 1.8 mm. Average position and rotation values for the motion of the L2 vertebral body relative to L3 for walking are given in Table 1. Schematics of the segment motion during walking are shown in Figure 5.

The variation in range of facet motion during walking was 1.3 to 5.4 ± 1.3 mm between animals. For each

Table 1. Average Vertebral Body Motion and Facet Motion During Walking Maneuver (n = 22). Ranges of Motion Illustrate the Variability Between Animals

	Body Motion (mm)	Body Rotation (degrees)	Facet Motion (mm)
X	0.86 ± 0.48	0.95 ± 0.37	0.63 ± 0.31
range:	(0.3–1.8)	(0.4–1.57)	(0.25–1.33)
Y	1.78 ± 1.18	0.57 ± 0.18	2.0 ± 1.2
range:	(0.7–5.5)	(0.3–0.94)	(0.5–5.4)
Z	1.15 ± 0.35	1.50 ± 0.53	1.0 ± 0.34
range:	(0.6–1.7)	(0.7–2.92)	(0.44–1.66)

individual animal, however, the range of facet motion was less varied and had an average variation of ±0.5 mm. Because the canine lumbar facets are primarily aligned in the sagittal plane, during walking the facet surfaces glide an average (over all animals) of 3.4 ± 1.3 mm on each other, with a ventral to dorsal slope (Figure 4). A schematic of the facet motion during a gait cycle is shown in Figure 6. As expected, changes in motion at the facet level closely mirrored those of the vertebral bodies, the two being part of the same rigid body. There were slight differences however, consistent with different centers of rotation.

As the dog moved from a sitting position to walk, a large initial segmental motion and rotation change, about twice that seen in the normal gait cycle, occurred. Normal motion was seen within a few steps.

As the animals were raised from a four-legged stance to a hind-leg stance they tended to hunch their backs, and the vertebral body L2 was found to initially rotate in the sagittal plane an average of 3.5° ± 2.8° with respect to the L3 vertebral body. As the dog relaxed and remained in this stance for 2 seconds more, this angle of the L2–L3 motion segment reduced to 2.2 ± 2.6°.

In the turning maneuvers, an average coronal plane segmental rotation of 3.2° (range, 0.3°–5.1°) was seen. An appreciable and varied amount of flexion, 1.9° ± 2.7°, also accompanied the lateral bending rotations. The average amount of coronal plane segmental rotation varied markedly between animals (±1.8°) and between successive tests on the same animal (±1.1°).

■ **Discussion**

There have been previous animal models examining articular kinematics; however, most involved an investigation of gross joint motion in one or two planes, or surgery with various degree of synovium damage.[1,2,20,24,30] Kinzel et al.[13,14] first designed the type of instrumented spatial linkage employed in this study. They rigidly fixed it to the bones of the canine shoulder and monitored the motion of the scapula over the humeral head as the dog walked on a treadmill. Keller et al.[12] used an *in vivo* mechanical loading apparatus to load and measure the stiffness of the porcine lumbar spine. They found that the mechanical measurements made differed significantly *in vivo* versus
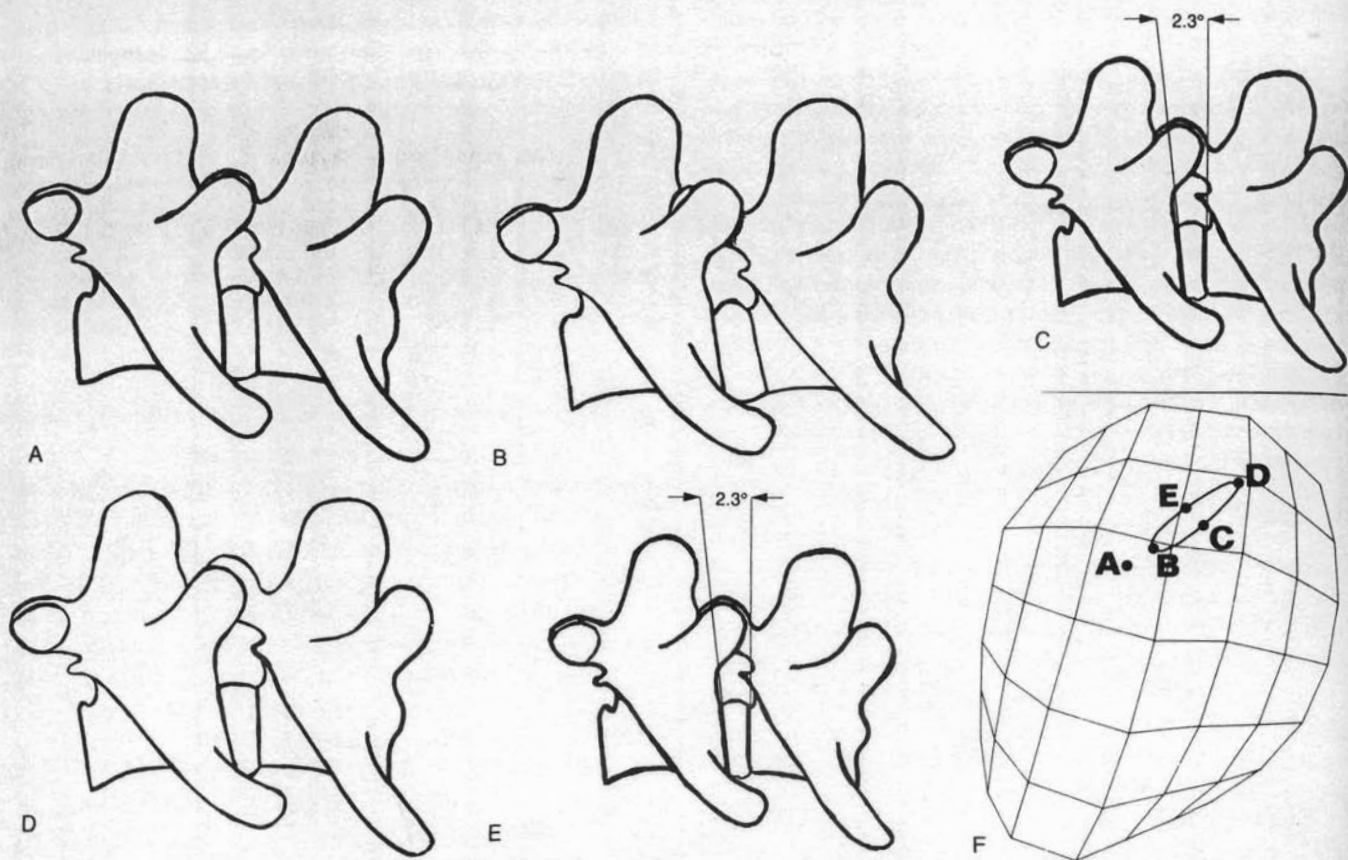
Figure 5. Typical motion of the vertebral bodies during normal gait. The differences in the cartoon drawings have been exaggerated to illustrate the trends more clearly. **A,** Vertebral body positions as the animal stands statically. Inferior articular process would have a locus at point A on the facet map **F. B,** Vertebral bodies at the beginning of the gait cycle with facet point locus at point B of the facet map. **C,** Position of the vertebral bodies in the middle of the gait cycle as indicated by point C in facet map **F. D,** Positions of the vertebral bodies at the peak of the gait cycle (point D of **F**) showing the compression of the intervertebral disc and facet excursion. **E,** Vertebral bodies at the final midpoint of the gait cycle (point E of **F**), very similar to point C except slightly more extension. **F,** Image of the superior articular process (as shown in Figure 4A) with positions of the gait cycle marked to correlate with vertebral body positions.

in vitro. These results demonstrate the importance of *in vivo* testing when investigating the biomechanics of the lumbar spine. Investigators have noted the lack of *in vivo* biomechanical data for the canine lumbar spine.[6,30] *In* *vivo* data are important when attempting to correlate biochemical changes with mechanical changes in disc degeneration models.[6,30] The *in vivo* method used in this study quantifies the motion that the vertebral bodies
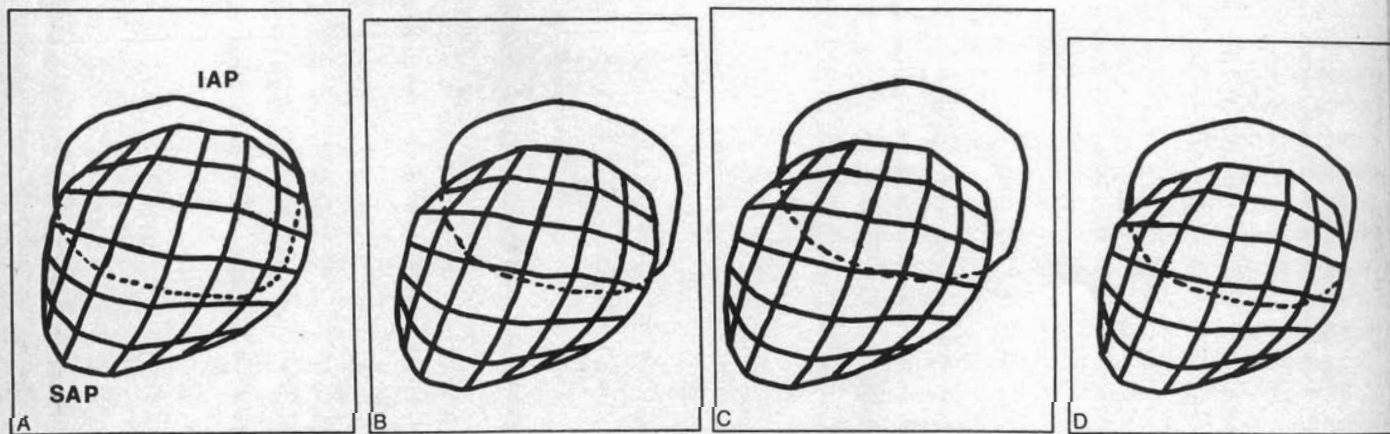

Figure 6. Motion of the superior facet surface viewed laterally (as shown in Figure 4A) during gait is shown by these four figures. **A,** The position of the inferior articular process (IAP) is shown relative to the superior articular process (SAP) for point B of the facet map in Figure 5F. **B,** Inferior articular process orientation for point **C** of the gait cycle shown in the facet map. **C,** The position of the superior facet surface at point D of Figure 5F. **D,** Orientation of the superior facet in the final position of the gait cycle (E of Figure 5F).

experience normally. This in turn will assist other researchers by defining the proper loads to apply (based on the motion) to motion segments being tested *in vitro*. The ISL used in this study has an accuracy of 0.7 mm when measuring the displacement between two bony landmarks during motion. The facet motion measured ranged up to 5 mm, which gives an ISL displacement measurement accuracy of 14% of the full range. These data imply that the absolute location of one facet surface with respect to the opposing facet surface can be located to within 0.7 mm. The repeatable accuracy of the ISL in measuring the spatial position of one body with respect to another was 0.5 mm and, with a corresponding maximum vertebral body range of motion of 5.5 mm, the ISL accuracy was 9% of the full range. The ISL accuracy in rotation was 0.6° and when compared with the maximum vertebral body walking rotation range of 2.9° the ISL accuracy was 20% of the full range.

When attempting to measure small *in vivo* intervertebral motions by the described method, certain problems arise, three of which warrant discussion. The most severe problem was inaccurate pin placement resulting in canal compromise and ultimately paralysis of one animal. Before attempting the pin insertions intraoperatively, the surgeon involved perfected his approach and insertion method on several cadaveric canine specimens. Use of fluoroscopy would reduce problems with pin placement. A second problem involved the choice of anesthetics used when exposing the implanted pins before ISL attachment on the day the animal was tested. A general anesthetic (atropine and Surital) was used; however, the recovery time (to a state where they could walk without staggering) varied from 2 to 4 hours. More recently we have adopted a policy of using gas (halothane), which gives a much more rapid anesthesia recovery. The local anesthetic (bupivacaine 1%) used to anesthetize the skin or pin exit area should be used liberally to insure no motion artifact from pain. The third problem area questions the existence of surgical artifact on the motion being measured. The effects of capsular contraction, pin placement, reflex pain mechanisms, and scar tissue for long-term studies all could influence the motion of the spine. Measurements after 4 weeks of pin implantation using our early surgical procedures showed reduced motion thought to be artifact. This is not a problem for short-term (<7 days) measurement, but would be important for longer-term measurements. We are continuing studies to minimize this effect. Recent adaptations of the pin placement method allow for the percutaneous placement of the pins, which should significantly reduce the surgical trauma and pain. It is hoped that this method will allow staged experiments with little or no surgical artifact. Another method being considered is mounting the ISL on spinous process pins. This technique would be convenient and would help eliminate scar tissue formation and muscular trauma.

During normal walking, the facet motion was concentrated within the cephalad half of the facet surface of the superior articular process. The ranges were large, but the individual anatomy of the dogs and gait speeds varied considerably. The 3.4-mm average displacement during walking represents approximately 35% of the facet surface. Each gait cycle is approximately 1.5 seconds in duration, resulting in an average relative surface velocity of $2 \times 3.4/1.5 = 4.6$ mm/sec.

Because the facet cartilage is thickest in the center, any motion significantly displaced from the center area may have implications in the pathogenesis of degenerative joint disease.[17,19] These results show a change in body orientation between neutral standing posture and the average posture during walking. This change indicates that during walking a different portion of the facet may be loaded vs. when the animal is standing. The walking data fit closely with the work of Buttermann et al.,[5] where strain gages were placed on canine facet processes *in vivo*, and the forces generated at the articular process during normal ambulation are measured. They described an approximately 3- to 6-mm loop of contact force migration during the normal gait cycle. Similarly, different resultant contact sites were described for neutral standing and walking activities. Motion as well as peak contact pressure areas shift from the upper half to the lower margin of the same surface as the dog moves from flexion to extension.[5] The movement of the dog from a sitting position to walking showed initial large displacements and rotations, which probably indicates larger loads on the spine when changing positions.

There were large variations in data from the left and right turn tests. The animals were coaxed into turning with food presented to them from behind; thus each dog displayed variable effort in the turning tests. The food was presented low to the floor, which probably accounts for the flexion component seen with the turning tests.

As the animals were raised to their hind legs, the L2–L3 motion segment posture changed as the dog's spine actually moved into flexion. If the dog was held up for a few seconds longer, however, it seemed to relax, and the flexion angle reduced by 1.3°. As with turning, the intra-animal and interanimal variation in motion segment behavior during this maneuver was high. Some dogs seemed to hunch up rigidly and others hunched up but soon relaxed. We assume this motion change is due to muscle relaxation; the test demonstrates that muscle action appears to affect the spine segment motion, as expected.

The methodology described here enables the documentation of three-dimensional motion of the *in vivo* canine spine segment and facet motion.

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