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Journal of Biomechanics 37 (2004) 205–212

JOURNAL
OF
BIOMECHANICS

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Structural behavior of human lumbar spinal motion segments

Mack G. Gardner-Morse*, Ian A.F. Stokes

Department of Orthopaedics and Rehabilitation, University of Vermont, Stafford Hall, Burlington, VT 05405-0084, USA

Accepted 20 October 2003

Abstract

The objectives of this study were to obtain linearized stiffness matrices, and assess the linearity and hysteresis of the motion segments of the human lumbar spine under physiological conditions of axial preload and fluid environment. Also, the stiffness matrices were expressed in the form of an 'equivalent' structure that would give insights into the structural behavior of the spine. Mechanical properties of human cadaveric lumbar L2-3 and L4-5 spinal motion segments were measured in six degrees of freedom by recording forces when each of six principal displacements was applied. Each specimen was tested with axial compressive preloads of 0, 250 and 500 N. The displacements were four slow cycles of ±0.5 mm in anterior–posterior and lateral displacements, ±0.35 mm axial displacement, ±1.5° lateral rotation and ±1° flexion-extension and torsional rotations. There were significant increases with magnitude of preload in the stiffness, hysteresis area (but not loss coefficient) and the linearity of the load-displacement relationship. The mean values of the diagonal and primary off-diagonal stiffness terms for intact motion segments increased significantly relative to values with no preload by an average factor of 1.71 and 2.11 with 250 and 500 N preload, respectively (all eight tests $p<0.01$). Half of the stiffness terms were greater at L4-5 than L2-3 at higher preloads. The linearized stiffness matrices at each preload magnitude were expressed as an equivalent structure consisting of a truss and a beam with a rigid posterior offset, whose geometrical properties varied with preload. These stiffness properties can be used in structural analyses of the lumbar spine.

Keywords: Lumbar spine; Motion segment; Stiffness matrix; Finite element analysis

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1. Introduction

The mechanical function of the spine is the summation of the behavior of its individual motion segments, where a motion segment is a structural unit of the spine consisting of two vertebrae and the intervening soft tissues (Fig. 1). Motion segment behavior is a key component of biomechanical analyses of the spine, including analyses of spinal loading (Stokes and Gardner-Morse, 2001), dynamics of injury (Kasra et al., 1992; Pankoke et al., 2001), spinal stability (Bergmark, 1989; Cholewicki and McGill, 1996; Gardner-Morse et al., 1995; Gardner-Morse and Stokes, 1998), and simulations of surgery (Aubin et al., 2003; Stokes and Gardner-Morse, 1993).

Isolated tests of motion segment behavior in individual degrees of freedom provide information that is specific to those degrees of freedom and cannot be generalized to three-dimensional analyses because of the interaction between degrees of freedom, called 'coupling' (Panjabi et al., 1976). A 6 × 6 stiffness or flexibility matrix is needed to describe how forces displace a vertebra relative to its fixed neighbor (Panjabi et al., 1976).

In general a 6 × 6 stiffness matrix has 36 terms. The number of independent stiffness matrix terms is reduced to 21 by consideration of matrix symmetry required by conservation of energy if the material properties are linear. Matrix symmetry results in complementary pairing of off-diagonal terms hence $k_{12}=k_{21}$, etc., in Fig. 2. Sagittal plane symmetry requires that nine of the 21 terms are zero (terms for forces expected to be zero for displacements within the sagittal plane, e.g. no lateral force associated with axial compression, hence k_{13} and $k_{31}=0$, etc.). This leaves 12 nonzero stiffness

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*Corresponding author. Tel.: +1-802-656-2250; fax: +1-802-656-4247.

E-mail address: mack.gardner-morse@uvm.edu
(M.G. Gardner-Morse).

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doi:10.1016/j.jbiomech.2003.10.003

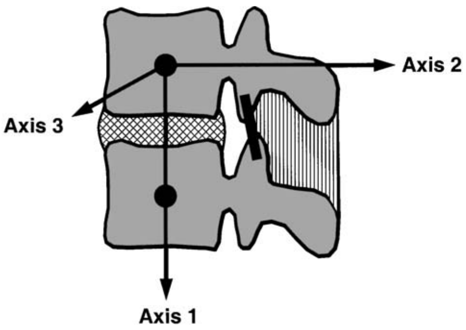

Fig. 1. Motion segment considered as a 2-node element. Nodes are at vertebral body centers. The axis numbering convention follows that normally used in finite element analyses. The lower vertebra was constrained during the tests while displacements were applied to the upper vertebra.

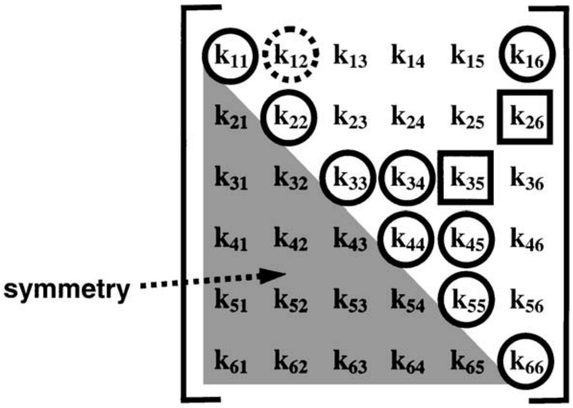

Fig. 2. Terms in the motion segment stiffness matrix. The six diagonal terms are those stiffness terms that relate forces or moments to the co-linear displacements or rotations. There is symmetry about the diagonal of the off-diagonal terms (in the shaded area), hence $k_{53} = k_{35}$, etc. The un-marked terms are expected to be zero based on sagittal plane motion segment symmetry. The terms k_{35} and k_{26} (marked by squares) are those identified by Goel (1987) as "primary" off-diagonal terms. The other three circled off-diagonal terms are associated with an antero-posterior offset of the structural axis from the vertebral body centers. The dashed circle identifies the coupling term (axial compression, anterior shear) that was found not to be significantly different from zero. Degrees of freedom 1–3 correspond to translations, and 4–6 correspond to rotations, with the sequence indicated in Fig. 1.

terms (Fig. 2). Goel (1987) defined a simplified stiffness matrix for the motion segment with six diagonal terms (relating co-linear displacements or rotations) and two "primary" off-diagonal terms, assuming that the motion segment had beam-like behavior. The two primary off-diagonal terms relate the anterior–posterior (A–P) shear forces to the applied flexion-extension rotations (or the complementary flexion-extension moments to A–P shear displacements) and lateral shear forces with lateral bending rotations (or the complementary lateral bending moments to lateral shear displacements). This beam-like behavior requires that the motions segment's axis system be aligned with its structural axis.

Since the motion segment has two vertebrae, each having six degrees of freedom, it requires a 12×12 stiffness matrix. This matrix can be derived from the 6×6 matrix for one vertebral center moving relative to a fixed adjacent vertebra, by using the principle of force equilibrium, compatible with the specified distance between the two vertebral centers (Gardner-Morse et al., 1990).

A shear beam with a rigid A–P offset was proposed by Gardner-Morse et al. (1990) as an approximate representation of an experimental stiffness matrix. This 'equivalent' beam has seven independent parameters, compared with up to 12 terms in the experimental stiffness matrix (Fig. 2). In this paper we propose an extension of that method, that also includes a truss element, thus permitting a closer approximation to the experimental data.

There are several limitations of the existing human motion segment experimental stiffness data, such that they probably do not accurately represent in vivo behavior. Most reported data do not include all six degrees of freedom (Berkson et al., 1979; Nachemson et al., 1979; Schultz et al., 1979), were obtained without physiological levels of axial compression and were performed with the specimen not surrounded by physiological isotonic fluid (e.g. Panjabi et al., 1976). Physiological axial compressive preload is known to increase stiffness by a factor of two or more (Edwards et al., 1987; Janevic et al., 1991; Gardner-Morse and Stokes, 2003) and may reduce the amount of load-displacement nonlinearity (Janevic et al., 1991; Gardner-Morse and Stokes, 2003). Discs in a physiological saline bath have greater hydration than discs that are just exposed to saline spray and wrap (Pflaster et al., 1997), and this increased hydration affects the disc biomechanics (Race et al., 2000; Costi et al., 2002). The increased hydration may also increase the repeatability of the load-displacement behavior with slow cyclic loading (Gardner-Morse and Stokes, 2003).

This paper reports the stiffness matrix and other properties of human lumbar motion segments tested with slow-rates of displacement, to obtain the quasi-static stiffness response of the motion segments, and with small displacements, to approximate the assumption of linear load-displacement behavior.

The purposes of the study were:

1. Quantify the effects of 0, 250 and 500 N axial compressive preload on the motion segment stiffness matrix, and on the hysteresis and linearity of the load-displacement relationship. The effect of preload was determined for intact motion segments and in isolated intervertebral discs.
2. Examine whether the stiffness matrix terms correlated with physical dimensions of the motion