ELSEVIER

PII: S002-9290(97)00055-9

J. Biomechanics, Vol. 30, No. 9, pp. 975–978, 1997
© 1997 Elsevier Science Ltd. All rights reserved
Printed in Great Britain
0021-9290/97 $17.00 + .00

TECHNICAL NOTE

A METHOD FOR MEASURING EXTERNAL SPINAL LOADS DURING UNCONSTRAINED FREE-DYNAMIC LIFTING

Fadi A. Fathallah,* William S. Marras, Mohamad Parnianpour and Kevin P. Granata

Biodynamics Laboratory, The Ohio State University, Columbus, OH, U.S.A.

Abstract—Biomechanical lifting models often require the knowledge of the applied trunk moments and forces for model validation purposes and/or to determine loading levels experienced at various joints of the body. Trunk kinetic data under dynamic exertions are commonly difficult to attain without restrictive anatomic/anthropometric assumptions and cost or constraining body motion. The main objectives of the study were to present a new technique for determining continuous three-dimensional forces and moments about the L5/S1 spinal joint, and to validate the technique and assess its applicability under lifting situations. A combination of a force plate and two electrogoniometers facilitated the determination of trunk kinetics about L5/S1. An apparatus was devised to allow the application of various *actual* moments that were compared to their corresponding *predicted* moments. The results showed that, over all the conditions considered, the average percent error in estimating the actual applied moment(s) was about 4% (2.3 S.D.), with a test–retest reliability approaching unity. Given such agreement, along with the relative ease and directness of the method, it is believed that this approach should be applicable under most lifting conditions. The technique offers a fairly accurate measure of trunk moments without the need for constraining the motion of *any* body joint. © 1997 Elsevier Science Ltd

Keywords: Spinal load, Lifting; Force plate; Trunk kinetics.

INTRODUCTION

Several modeling approaches use external loads (net reaction moments and forces) for quantifying and validating the stresses experienced by the spinal structure during task execution (Granata and Marras, 1995; Plamondon *et al.*, 1996). External loads are commonly determined via various techniques such as dynamometers, video-based motion systems, and 'force plates'. Force plates measure the net reaction forces and moments at the feet rather accurately without the extensive data reduction effort common to video-based techniques or the restrictions of the dynamometers (e.g. joint motion restriction, motion type, etc.).

Granata *et al.* (1996) presented a technique that uses the 3-D net reaction loads provided by the force plate to estimate the moments and forces at the L5/S1 joint. In that study, the L5/S1 joint was assumed to be at a *fixed position* relative to a force plate. However, in order to investigate *unconstrained* free-dynamic conditions, the pelvis is expected to be freely moving with respect to the force plate. Hence, it is important to continuously document the relation of the moving (L5/S1) coordinate system to that of the fixed system (force plate). The two main objectives of this study were (1) to develop a technique for determining the continuous 3-D forces and moments about the L5/S1 spinal joint, and (2) validate the technique and assess its applicability to lifting conditions.

METHOD

A 'free body diagram' of the lower body segment below the L5/S1 joint is represented in Fig. 1(a). The distal end of the segment was considered at the force plate (FP) (Bertec 4060A; Bertec, Worthington, Ohio) and its proximal end at the L5/S1 joint. The forces and moments measured by the FP can then be written as

$$\mathbf{M}_{FP} = \mathbf{M}_{L5} + \mathbf{M}_{L} + [(m\,\mathbf{a}_{Lcm}) \times \mathbf{R}_{FPL}] + (\mathbf{F}_{L5} \times \mathbf{R}_{FPL5}),$$
$$\mathbf{F}_{FP} = \mathbf{F}_{L5} + (m\,\mathbf{a}_{Lcm}), \quad (2)$$

where
$\mathbf{M}_{FP}$ = moment vector acting at the FP; distal end,
$\mathbf{M}_{L5}$ = moment vector acting at the L5/S1 joint; proximal end,
$\mathbf{M}_{L}$ = moment vector acting at the center of mass of the lower body segment (L) due to angular acceleration of the lower extremity,
m = mass of the lower body segment,
$\mathbf{a}_{Lcm}$ = acceleration of the center of mass of the lower extremity,
$\mathbf{R}_{FPL}$ = position vector between the FP and L
$\mathbf{R}_{FPL5}$ = position vector between the FP and the L5/S1 joint,
$\mathbf{F}_{FP}$ = force vector acting at the FP,
$\mathbf{F}_{LP}$ = force vector acting at the L5/S1 joint.

Equations (1) and (2) can be rewritten as follows:

$$\mathbf{M}_{L5} = \mathbf{M}_{FP} - \mathbf{M}_{L} - [(m\,\mathbf{a}_{Lcm}) \times \mathbf{R}_{FPL}] - (\mathbf{F}_{L5} \times \mathbf{R}_{FPL5}), \quad (3)$$

$$\mathbf{F}_{L5} = \mathbf{F}_{FP} - (m\,\mathbf{a}_{Lcm}). \quad (4)$$

The forces and moments acting at the L5/S1 joint include those generated by the upper body segment and any applied external loads (e.g. lifted box). The weight of the lower body segment (and upper body) can be systematically eliminated using the *zeroing* option on the FP (Bertec 4060A user's manual). Therefore, the moment vector about L5/S1 would be overestimated by a magnitude of ($\mathbf{M}_{L} + [(m\,\mathbf{a}_{Lcm} \times \mathbf{R}_{FPL}]$). Similarly, the force vector F_{L5} would be overestimated by a magnitude of $m\,\mathbf{a}_{Lcm}$. However, several studies have demonstrated that the *inertial* effects of the lower body segments played a minimal role in the net moment generated, especially when 'back lifts' are performed (Lindbeck and Arborelius, 1991; Plamondon *et al.*, 1996). Hence, in this study, it was assumed that the unaccounted moment and force vectors due to lower body dynamics would constitute minimal contribution to the total moment and force generated at L5/S1. Therefore, equations (3) and (4) would be reduced as follows:

$$\mathbf{M}_{L5} \approx \mathbf{M}_{FP} - (\mathbf{F}_{L5} \times \mathbf{R}_{FPL5}), \quad (5)$$

$$\mathbf{F}_{L5} \approx \mathbf{F}_{FP}. \quad (6)$$

The FP measures the two vectors F_{FP} and M_{FP}, hence, the only unknown is the position vector between the FP and the L5/S1 joint (R_{FPL5}). Two goniometers were developed in order to determine this vector: (1) The L5/S1 3-D Locator, and (2) the Pelvic Orientation Monitor (POM) [see Fig. 1(b)].

Received in final form 17 *April* 1997.
*Address correspondence to: Fadi Fathallah, Liberty Mutual Research Center, 71 Frankland Road, Hopkinton, MA 01748, U.S.A.