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TECHNICAL NOTE

A METHOD FOR MEASURING EXTERNAL LOADS DURING DYNAMIC LIFTING EXERTIONS

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Abstract—Biomechanical analyses of lifting exertions often require measured values of applied trunk moments and forces as baseline or validation data. Accurate measures of the trunk kinetic data are difficult to achieve from dynamic exertions without significant approximation, cost, or motion constraints. The purpose of this effort was to develop and validate a means to directly measure multi-dimensional, trunk moments which occur during dynamic lifting exertions. Force plate reaction loads, coupled through a lower-body isolation structure designed to fasten the hips and legs into a known static position, were employed to compute the moment vectors about the lumbar spine. Results demonstrate the applied moments about the lumbo-sacral junction of the spine can be accurately measured from a single force plate, allowing biomechanical evaluation of dynamic lifting exertions without constraining the motions of the upper body. Copyright © 1996 Elsevier Science Ltd.

Keywords: Low-back; Lifting; Force plate.

INTRODUCTION

Measured force and moment data typically form the baseline or validation component for biomechanical analyses. Measured kinetic data must accurately reflect the applied dynamics of the exertion without influencing the motions or biomechanics of the exertion. Biomechanical measurements of external forces and moments generated by the trunk during lifting exertions have often involved significant approximation, complexity and expense. A simpler, direct measure of trunk kinetics may improve the accessibility of accurate data representing lifting dynamic.

External loads on the lumbar spine have been estimated from video motion analysis and inverse mechanics (Chaffin, 1969; Freivalds *et al.*, 1984; Gagnon and Smyth, 1992; Goel *et al.*, 1991; McGill and Norman, 1985, 1986), but the technique can be expensive, complex, and inexact. Kromodihardjo and Mital (1986) found that dynamic ground reaction forces estimated from motion analyses correlation with force plate data at 0.65. Thus, validation of biomechanical analyses becomes difficult since one cannot achieve accurate measures of external trunk load. Miller *et al.* (1980) indicated kinetic analyses from video techniques generated inertial results within an order of magnitude of the actual levels. Needless to say, it is often desirable to achieve baseline errors much less than an 'order of magnitude' to represent the applied loads. Considering the analytical and inertial errors as well as the cost of video motion analysis systems, one may desire a direct measure of external trunk loads during dynamic lifting exertions.

Direct measurements of external trunk moments have been achieved by measuring the forces applied by subjects against a harness or experimental structure (Granata and Marras, 1993; Marras *et al.*, 1984; Pope *et al.*, 1986). Although the technique permitted controlled measurements of trunk kinetics, Granata (1993) demonstrated the method also led to muscle activity patterns which were significantly different than those associated with unconstrained lifting exertions. Therefore, the measurement technique confounded the data representing neuro-muscular control and biomechanical loading.

Force plates provide an accurate measure of dynamic trunk loads, but have been employed only in combination with motion analysis or in multiple force plate configurations. Freivalds *et al.* (1984) utilized a force plate to measure the ground reaction force, but could provide no estimate of external trunk moments. Thelen *et al.* (1991, 1994) measured applied trunk forces and moments by means of two force plates, one at the subjects' feet, another at the pelvis. Their method allowed direct measurement of trunk kinetics, but may be simplified to achieve accurate results from a single force plate.

Our objective was to develop a method to accurately measure applied trunk moments during dynamic lifting exertions. The method was designed to assure the measurement system did not interfere with trunk motion or influence muscle coactivity. The technique is presented to suggest a simple and accurate measure of applied trunk moments permitting examination of trunk biomechanics during dynamic lifting exertions.

METHODS

A lower-body isolation structure (LBIS) was constructed to hold a subject's hips in a fixed position above the feet and resist pelvic and lower body motion. Belts, three inches wide, were employed to hold the hips and upper legs against back plates, thereby preventing significant movement of the legs and hips during the exertions. When strapped into the structure, subjects were free to move their upper body without constraint or interference (Fig. 1). The LBIS was fixed to the top surface of a force plate (Bertec 4060A) by means of removable clamps. External forces and moments applied to the upper body of the subjects, including inertial dynamics, were thereby transferred directly to the force plate through the subjects' legs and LBIS.

One may compute the external forces and moments generated about the low-back from dynamic force plate data and a vector describing the static location of the lumbo-sacral spine. Assume an external force of magnitude **F** passes through the trunk with an arbitrary vector direction. Define **r** as the vector from the

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Fig. 1. A lower-body isolation structure (LBIS) was constructed to fasten the subject's legs and hips into a static position over the center of the force plate and transfer all forces and moments into the force plate. The upper-body is completely free to move. The pictured subject is also wearing a lumbar motion monitor to measure trunk motions.

center of the force plate to a point of application of the force $\mathbf{F}$ (Fig. 2). The sum of static weights of individual segments of the upper body, $\mathbf{W}_U$, and the sum of dynamic forces from the upper body segment masses, $\mathbf{F}_U$ also load the force plate from a vector distance representing the instantaneous center of force $\mathbf{r}_U$. Similarly, net static and dynamic forces from the lower body, $\mathbf{W}_L$ and $\mathbf{F}_L$, can be described at a vector distance $\mathbf{r}_L$ from the center of the force plate.

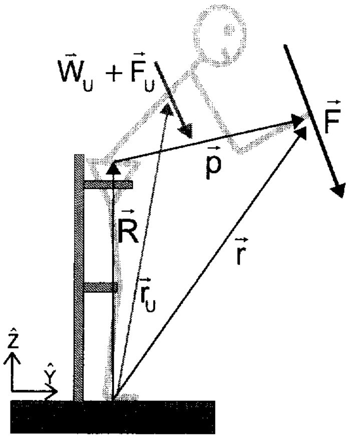

Fig. 2. Moments about the L5/S1 level of the spine were computed from vector mechanics using ground reaction force and moment data from a force plate and the measured elevation of the L5/S1 junction above the center of the force plate.

$$\mathbf{F}_{FP} = \mathbf{F} + (\mathbf{W}_U + \mathbf{F}_U) + (\mathbf{W}_L + \mathbf{F}_L), \tag{1}$$

$$\mathbf{M}_{FP} = \mathbf{r} \times \mathbf{F} + \mathbf{r}_U \times (\mathbf{W}_U + \mathbf{F}_U) + \mathbf{r}_L \times (\mathbf{W}_L + \mathbf{F}_L). \tag{2}$$

Since the lower body is held static by the LBIS, the dynamic forces $\mathbf{F}_L$ must be zero. If the subject is centered over the force plate, then $\mathbf{r}_L$ is vertical, and the force plate moment due to the lower body is negligible.

Allow $\mathbf{p}$ to represent the distance vector from the lumbosacral junction to the point of application of the external force $\mathbf{F}$. Let $\mathbf{p}_U$ describe the vector distance from L5/S1 to the upper body force equivalents $\mathbf{W}_U$ and $\mathbf{F}_U$. The moments about L5/S1 may be expressed as

$$\mathbf{M}_{LS} = \mathbf{p} \times \mathbf{F} + \mathbf{p}_U \times (\mathbf{W}_U + \mathbf{F}_U). \tag{3}$$

Describe the line from the center of the force plate to the lumbo-sacral junction with a vector $\mathbf{R}$. Note that $\mathbf{r}$ is the vector sum of $\mathbf{p}$ and $\mathbf{R}$ (Fig. 2). A similar relation may be employed to determine $\mathbf{p}_U$ from $\mathbf{r}_U$.

$$\mathbf{p} = \mathbf{r} - \mathbf{R}, \tag{4}$$

$$\mathbf{p}_U = \mathbf{r}_U - \mathbf{R}. \tag{5}$$

Table 1.

Applied Loads		Force Plate Measures			Computed
F_Y	F_Z	F_Y	F_Z	M_X	M_X
0	0	1.2	0.9	1.1	1.8
0	-96	0.4	-96.1	-62.1	-62.1
0	-206	0.7	-205.7	-127.4	-125.6
F_Y @ Z=0.6m					
96	0	95.5	1.3	-59.6	-1.4
96	-96	95.2	-95.9	-124.4	-65.7
96	-206	97.0	-205.1	-188.1	-128.9
F_Y @ Z=1.2m					
96	0	95.4	1.1	-122.1	-63.8
96	-96	96.3	-96.0	-185.2	-126.5
96	-206	95.8	-206.6	-243.0	-184.6

Applying these relations into the lumbar moment equation (3), one may express the moment about the lumbar spine in terms of $\mathbf{r}$, $\mathbf{r}_U$ and $\mathbf{R}$.

$$\mathbf{M}_{LS} = \mathbf{r}\times\mathbf{F} + \mathbf{r}_U\times(\mathbf{W}_U + \mathbf{F}_U) - \mathbf{R}\times(\mathbf{F} + \mathbf{W}_U + \mathbf{F}_U). \qquad (6)$$

Forces and moments measured by the force plate described in equations (1) and (2) may be employed to simplify the lumbar moment equation (6).

$$\mathbf{M}_{LS} = \mathbf{M}_{FP} - \mathbf{R}\times(\mathbf{F}_{FP} - \mathbf{W}_L). \qquad (7)$$

Since the subject is centered over the force plate, $\mathbf{R}$ is vertical. Considering also that the static weight of the lower body, $\mathbf{W}_L$ is vertical, the $\mathbf{W}_L$ term does not contribute to the measured lumbo-sacral moment $\mathbf{M}_{LS}$. Thus, lumbar moments may be expressed in terms of measured force data and $\mathbf{R}$.

$$M_{LSx} = M_{FPx} + R_z F_{FPy}, \qquad (8)$$

$$M_{LSy} = M_{FPy} - R_z F_{FPx}, \qquad (9)$$

$$M_{LSz} = M_{FPz}. \qquad (10)$$

The force plate measures F_{FPx}, F_{FPy}, F_{FPz}, M_{FPx}, M_{FPy}, M_{FPz} directly. Therefore, simple measurement of the constant elevation R_z permits immediate calculation of the trunk moment $\mathbf{M}_{LS}$.

A static validation of the method was performed by applying known moments to the top of the LBIS, i.e. the hypothetical position of the lumbo-sacral junction, then analyzing the results to determine whether the data predicted the applied kinetics accurately. A calibration bar was attached to the top of the LBIS extending horizontally forward to provide a moment arm from which weights could be suspended. Weights of 0, 96 and 206 N were hung from the calibration bar at a distance of approximately 0.6 m forward of the LBIS, to generate nominal moments of 0, − 58 and − 124 N m, about the right lateral axis, i.e. X-axis. Horizontal forces of 0 and 96 N were applied to the LBIS by a cable which extended forward from the structure, passing over a pulley to support the weight. The horizontal forces were applied at two elevations, 0.6 and 1.2 m above the force plate. This configuration allowed the horizontal forces to contribute moments of 0, − 58 and − 124 N m about the X-axis of the force plate. Various combinations of vertical and horizontal loads were applied to examine the contributions of the forces, and the behavior of the moments predicted about a reference axis at an elevation of 0.6 m simulating the location of the lumbo-sacral spine. Neutral values of the weight and moments from the LBIS frame were established as a baseline by auto-zeroing the force plate prior to the application of the forces.

Force plate data were digitized using a 12 bit, A/D system (DT2821) and collected on a portable computer. Raw data were converted to three-dimensional forces and moments as prescribed by the force plate manual. The conversion software was written so as to incorporate the vector mechanics described above. Output represented the measured forces and moments about a specific elevation, i.e. about the lumbo-sacral junction of a hypothetical subject.

RESULTS

When no horizontal forces were applied to the system, the moments at the hypothetical lumbo-sacral spine were identical to those measured at the force plate surface. Because the applied forces were purely vertical and the vector locating the lumbo-sacral junction relative to the force plate had no vertical (x or y) components, the moments were not influenced by elevation (Table 1).

Application of horizontal forces at the reference axis elevation of 0.6 m contributed to the moments measured at the force plate, but did not contribute to the computed moments at the reference axis. Since the horizontal moments were applied at the reference axis, the vertical lever arm distance from the reference axis was zero, thereby generating no significant moment. Consequently, moments predicted about the reference axis were nearly identical to values produced when purely vertical forces were applied.

When horizontal forces were applied at an elevation of 1.2 m, both the force plate and reference axis moments were affected. As expected, the contribution of F_Y to the moment at the force plate surface was twice that described in Table 1 because the vertical lever arm distance had doubled. The horizontal forces contributed a constant 59.6 ± 2.8 N m to the sagittal moment about the reference axis.

DISCUSSION

A set of mechanical equations has been presented to allow accurate determination of external trunk moments while subjects perform dynamic lifting exertions. An example of the sagittal moment generated by a subject lifting a 27 kg weight is illustrated in Fig. 3, and agrees with the dynamic load profiles

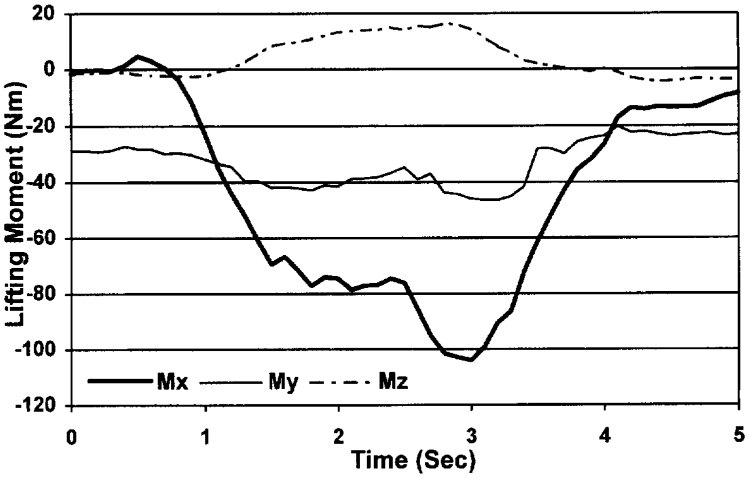

Fig. 3. Moments in each of the three dimensions can be determined as in this example of a dynamic sagittally symmetric lifting exertion.

and general magnitudes reported in the literature (Dolan and Adams, 1993; Jager and Luttman, 1989; McGill and Norman, 1986; Schipplein *et al.*, 1990). Although the equivalent moment arm from the lumbo-sacral junction to the net applied force may be impossible to measure because of the dynamic nature of the distributed mechanical system, the method computed it from the vector forces and moments recorded by the force plate. By constraining the hips and legs using the LBIS, forces applied above the hips were conserved and measured directly by the force plate at the subject's feet. The single, three-dimensional force vector reported by the force plate represents the vector sum of the dynamic forces from the applied exertion as well as the weight and inertial components from the trunk, arms and head. Errors associated with the need to estimate body segment masses and moments of inertia were eliminated.

Measurements of lifting exertions by this method were limited because the hips and legs were constrained. This was necessary for two reasons. First, the location of the lumbo-sacral junction relative to the center of the force plate must be known. Second, lower body motion may contribute inertial forces to the net value measured by the force plate. Constraining the hips and legs accomodates both of these factors. Schipplein *et al.* (1990) demonstrated a clear interaction between the legs, hips and trunk mechanics during a lifting exertion, but conclude that the trunk generates lifting moments as much as an order of magnitude greater than the knees. Whereas the LBIS prevented simulation of whole-body lifting exertions, it did permit focused analyses of dynamic trunk biomechanics with increased accuracy and reduced complexity, expense and confounding influences of previous methods. Although this study examined the moments about a single axis, the data was sufficient to validate the mechanics which describe three-dimensional evaluation of dynamic lifting exertions.

The advantage to this method was that external loads were computed directly, kinetics of dynamic trunk exertions were simple to achieve, and there were no restrictions to upper body motions. Only one force plate was necessary to perform the measurement, and no expensive motion analysis systems or restrictive lifting frames were required. Construction of a LBIS was relatively simple, requiring only that the structure securely hold the subjects lower-body statically in place and that the LBIS and the subject be supported solely by the measurement surface of the force plate. Although this method was developed for the examination of external trunk kinetics, we believe it may be adapted for the biomechanical evaluation of other joints in the body.

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