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A comparison of instrumentation methods to estimate thoracolumbar motion in field-based occupational studies

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ABSTRACT

The performance of an inertial measurement unit (IMU) system for directly measuring thoracolumbar trunk motion was compared to that of the Lumbar Motion Monitor (LMM). Thirty-six male participants completed a simulated material handling task with both systems deployed simultaneously. Estimates of thoracolumbar trunk motion obtained with the IMU system were processed using five common methods for estimating trunk motion characteristics. Results of measurements obtained from IMUs secured to the sternum and pelvis had smaller root-mean-square differences and mean bias estimates in comparison to results obtained with the LMM than results of measurements obtained solely from a sternum mounted IMU. Fusion of IMU accelerometer measurements with IMU gyroscope and/or magnetometer measurements was observed to increase comparability to the LMM. Results suggest investigators should consider computing thoracolumbar trunk motion as a function of estimates from multiple IMUs using fusion algorithms rather than using a single accelerometer secured to the sternum in field-based studies.

1. Introduction

Low back pain (LBP) is a common work-related musculoskeletal disorder (MSD) with an estimated 1-month prevalence of 23.2% and lifetime prevalence ranging as high as 84% (Hoy et al., 2012; Walker, 2000). Occupational exposure to non-neutral trunk postures and manual material handling (MMH) activities may be associated with LBP (Coenen et al., 2013; da Costa and Vieira, 2010; Manchikanti, 2000; Hoogendoorn et al., 2000; Vieira and Kumar, 2004; van Oostrom et al., 2012). Evidence of these associations, however, is inconsistent (Roffey et al., 2010; Wai et al., 2010a, 2010b). In part, characterization of associations between non-neutral trunk postures and LBP has been limited by use of easily administered but imprecise and potentially biased self-report or observation-based exposure assessment methods (Burdorf and Van Der Beek, 1999; David, 2005; Li and Buckle, 1999; Vieira and Kumar, 2004).

Common approaches for directly measuring thoracolumbar trunk motion in a field setting include electrogoniometry and body mounted electromechanical sensors. The Lumbar Motion Monitor (LMM) is a field-capable, triaxial electrogoniometer used to directly measure kinematics of the thoracolumbar spine (Marras et al., 1992, 1995; Marras and Granata, 1995; Gill and Callaghan, 1996). The LMM is secured to the trunk of a worker using chest and pelvic harnesses and measures thoracolumbar angular displacement of the trunk relative to the pelvis in the three primary motion planes. With software, numerical differentiation of the angular displacement measurements is then used to obtain estimates of trunk angular velocities and angular accelerations in the three motion planes. Although the LMM has been used in numerous studies (e.g., Ferguson et al., 2002; Gallagher et al., 2002; Marras et al., 2004, 1999), its bulky size and limited range (i.e., through direct cable connection to a computer or through telemetry) make it impractical for prolonged field-based exposure assessments recommended to obtain stable and representative estimates of trunk motion during non-routinized work activities (e.g., construction and agriculture) (Trask et al., 2007).

Accelerometers (or inclinometers) have been used frequently in field-based research to obtain direct measurements of trunk motion over extended time periods (e.g., Fethke et al., 2011; Koehoorn, 2010; Paquet et al., 2001; Teschke et al., 2009; Van Driel et al., 2013; Wong et al., 2009). Trunk motion estimates have been reported using a variety of sensor configurations (e.g., dual axis or triaxial)

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and sensor placement strategies (e.g., one sensor placed on the anterior torso as in Fethke et al. (2011) vs. one sensor on the posterior torso as in Wong et al. (2009) vs. one sensor on the anterior torso combined with one sensor on the posterior pelvis as in Koehoorn (2010)). Axial rotations about the transverse plane, however, cannot be assessed through the use of an accelerometer alone, and the accuracy of accelerometer-based estimates in the flexion/extension (sagittal) and lateral bending (coronal) planes depends on the characteristics of the motion (static, quasi-static, or complex dynamic) (Amasay et al., 2009; Brodie et al., 2008; Godwin et al., 2009; Hansson et al., 2001).

Inertial measurement units (IMUs) have recently emerged as a potential alternative to accelerometers for measurement of human trunk motion in occupational settings. An IMU is a small and portable device that permits estimation of the spatial orientation of an object by combining the outputs of multiple electromechanical sensors (accelerometers, gyroscopes, and/or magnetometers) through recursive sensor fusion algorithms such as a Kalman filter or complementary weighting algorithm (Bachmann, 2000; Gallagher et al., 2004; Higgins, 1975; Kalman, 1960; Luinge and Veltink, 2005; Sabatini, 2006; Wagenaar et al., 2011; Yun and Bachmann, 2006). Theoretically, using sensor fusion algorithms for motion measurement can help overcome the limitations of each individual sensor component. For example, gyroscope measurements can be used to compensate for limitations of the accelerometer to more accurately measure motion in the flexion/extension and lateral bending planes under dynamic conditions, and magnetometers can provide orientation information necessary to make estimates of trunk motion in the axial rotation plane. Raw data streams from the individual sensor components may also be extracted for singular analysis.

Despite their unique capabilities and promise, few studies have used IMUs to directly measure thoracolumbar trunk motion in the field. One potential explanation for their limited use may be a lack of comparison to more widely known methods such as accelerometers or electrogoniometer systems such as the LMM. While many studies have examined the accuracy of IMU systems in comparison to optoelectric motion capture systems (Cuesta-Vargas et al., 2010) and/or have evaluated corrective factors for accelerometers (e.g., Van Driel et al., 2013), the potential benefit of using IMUs to estimate thoracolumbar motion in comparison to other field-capable systems remains unclear. For example, estimates of trunk motion can be made using information obtained from an IMU's accelerometer alone, from an IMU's accelerometer and gyroscope, or from the full complement of IMU sensors (i.e., accelerometers, gyroscopes, and magnetometers). Exploration of the different sensor configurations and processing methods possible with an IMU system will provide information about the potential advantages of IMU use in comparison to simpler options.

The objectives of this study were, therefore, to (i) compare estimates of thoracolumbar trunk motion obtained with a commercially available IMU system with estimates of thoracolumbar trunk motion obtained with a field-capable reference system, the LMM, and to (ii) explore the effect of alternative sensor configurations and processing methods on the agreement between LMM and IMU-based estimates of trunk motion during a simulated MMH task with both systems deployed simultaneously.

2. Methods

2.1. Participants

A convenience sample of 36 healthy, male participants (mean age = 24.9 years, SD = 4.5) was recruited from the University of Iowa community. Potential participants were excluded for any self-reported 1) physician-diagnosed MSDs of the back in the past six or fewer months, 2) orthopedic surgery of the back, 3) back pain in the past two weeks, or 4) chronic neurodegenerative disease (e.g., Parkinson's disease). All study procedures were approved by the University of Iowa Institutional Review Board and written informed consent was obtained prior to participation.

2.2. Experimental design

Participants completed a simulated MMH task in a laboratory setting. The MMH task required participants to manually move 4.5 kg plastic crates (42 × 35 × 27 cm) from a waist-high material feeder (Point A in Fig. 1, as depicted from above) to one of six potential unloading areas (Point B in Fig. 1). Two handholds were molded into each crate and used by workers for manual grasping. The six potential unloading areas varied across two factors: the unloading height (adjusted to each participant to be approximately waist height or knee height) and the total magnitude of axial rotation (twisting) needed to move a crate from the material feeder to the unloading area (90°, 135°, or 180°). The pace of the task was set to either 6 lifts/min or 3 lifts/min. Block randomization was used to assign each participant to one of the 12 task conditions (2 unloading heights × 3 axial rotation magnitudes × 2 work paces; 3 participants per condition). The modest crate weight and work pace levels were selected to ensure that the recommended weight limit of the NIOSH Lifting Equation was not exceeded when considering all combinations of the unloading height, amount of axial rotation, and work pace parameters (Waters et al., 1993).

2.3. Instrumentation and data processing

Angular displacements of the thoracolumbar region of the trunk in the flexion/extension, lateral bending, and axial rotation planes were estimated using two commercially-available instrumentation systems: the ACUPATH™ Industrial Lumbar Motion Monitor™ (Biomec Inc., Cleveland, OH) and the I2M Motion Tracking System (series SXT IMUs, Nexgen Ergonomics, Inc., Pointe Claire, Quebec). For each participant, one IMU sensor was secured to the anterior torso at the sternal notch and a second IMU sensor was secured to the posterior pelvis at the L5/S1 vertebrae. Standard procedures were used to outfit participants with the LMM as in previous studies (e.g., Marras et al., 1995). The LMM was calibrated prior to fitting by using procedures described in the LMM manual. Data streams obtained from the LMM included angular displacement (in degrees) of the trunk in the flexion/extension, lateral bending, and axial rotation planes. The LMM was connected to a computer using a communications cable and the data streams were sampled at

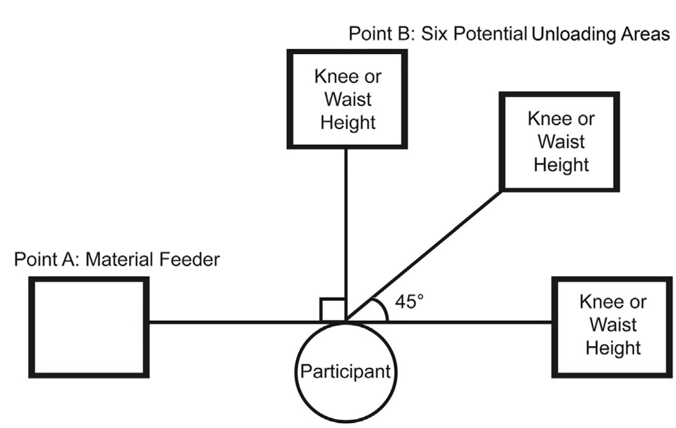

Fig. 1. Simulated manual material handling task positions.