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Validation of tri-axial accelerometer for the calculation of elevation angles

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ABSTRACT

One of the main issues in occupational studies focusing on musculoskeletal disorders of the upper extremity is how to best quantify workers' exposures to risk factors during a workday. Direct measurement is preferred because it is objective and provides precise measurements. To measure elevation angle exposure of the upper extremity, accelerometers are commonly used. The main problem with the use of accelerometers is the fact that they are sensitive to linear acceleration and can only assess two axes of rotation. In the present study the Virtual Corset, a pager-sized, battery powered, tri-axial linear accelerometer with an integrated data logger, was validated in vitro for the reconstruction of elevation angles under static conditions and angle error prediction under dynamic conditions. For static conditions, the RMS angle error was less than 1°. Under dynamic conditions the elevation angle error was influenced by the radius and angular acceleration. However, the angle error was predicted well with an RMS difference of 3°. It was concluded that the Virtual Corset can be used to accurately predict arm elevation angles under static conditions. Under dynamic conditions, an understanding of the motion being studied and the placement of the Virtual Corset relative to the joint are necessary.

Relevance to industry: A device is tested that could capture posture exposure of the shoulder at the workplace during a workday. Such exposure measurement can be used to test interventions and to develop preventive guidelines to reduce risk factors associated with musculoskeletal injuries of the upper extremity.

1. Introduction

Shoulder pathologies are included under the broad term of musculoskeletal disorders, which is defined by the United States Department of Labor as an injury or disorder of the muscles, nerves, tendons, joints, or cartilage when the event or exposure leading to the injury or illness is bending, reaching, twisting, overexertion, or repetition. The outcome may be sprains, strains, tears, soreness and pain (Bureau of Labor Statistics, 2006).

The United States Department of Labor has also reported that in 2005 there were a total of 1.2 million injuries and illnesses requiring days away from work in the private industry, with 30% due to musculoskeletal injuries. The event that resulted in the longest absences from work was repetitive motion, with shoulder injuries being responsible for more lost workdays than any other joint (Bureau of Labor Statistics, 2006). Additionally, Ohlsson et al. (1995) found that chronic exposure to arm elevation higher than 60° during a workday is associated with higher rates of shoulder injury, while Svendsen et al. (2004a,b) and Punnett et al. (2000) found that workers exposed chronically to arm elevation higher than 90° are more susceptible to shoulder injury.

Three main physical risk factors for musculoskeletal disorders have been identified in the workplace: force (intensity and duration), repetition, and posture (awkward and constrained) (Bernard, 1997). The assessment of occupational exposures to these risk factors in field settings is very challenging. Three methods are commonly used to determine exposure: (1) self-reporting, questionnaire and interview, (2) observational methods and (3) direct measurements (David, 2005; Li and Buckle, 1999). The first two methods are subjective whereas, direct measurement is objective and provides precise measurements; hence, it is usually preferred. However, factors such as the cost of equipment, need for trained technicians, time consuming equipment set-up and proper calibration, unsafe work environments (such as dust and chemicals), constrained recording area, and limited recording time, limit the usability of some of the high-end or sophisticated systems in the workplace, such as magnetic and optic 3D tracking devices.

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To overcome these disadvantages, low cost, body-mounted transducers combined with data loggers capable of whole day ambulatory recordings are used. For upper extremity exposure measurements, goniometers (Paquet et al., 2001) and inclinometers (Hansson et al., 2001a) have been used to estimate the arm elevation angles. An inclinometer is a transducer that measures the elevation/inclination angle relative to gravity. Different types of transducers have been developed and are used to measure elevation angle exposure such as the abduflex (Fernstrom and Ericson, 1996; Svendsen et al., 2005) consisting of mercury microswitches, Intometer (Sporrong et al., 1999) consisting of pressure transducers and distilled water, Physiometer (Vasseljen and Westgaard, 1997) consisting of electrolytic liquid level sensors, and linear accelerometers (Bernmark and Wiktorin, 2002; Estill et al., 2000; Hansson et al., 2006, 2001a; Moller et al., 2004; Mathiassen et al., 2003). Linear accelerometers are commercially available and are commonly used in evaluation of segments' posture by means of uni-axial (Paquet et al., 2001), bi-axial (Boonstra et al., 2006) and tri-axial (Hansson et al., 2001b) accelerometers.

However, many of these devices have limitations due to their construction. Most are big and clumsy with a cable connecting the transducers, which are placed on the body segment, and data loggers, which are usually worn on a belt at the waist. Some devices are complicated to mount and align with the coordinate system of the body segment. Others suffer from limited measuring range and/or low data collection sampling rates. Moreover, most of these devices are not available commercially. To the best of our knowledge there is one device with a built in data logger which is commercially available. The Virtual Corset (Microstrain, Inc., VT, USA) is a tri-axial linear accelerometer with no associated cables. However, the main problems with linear accelerometers are their sensitivity to linear acceleration and assessment of only two axes of rotation. Any linear acceleration besides gravity will bias the calculated elevation angles. To better understand the use of the Virtual Corset and the data that can be obtained with this device on the arm, laboratory testing was completed. The purpose of this study was to test and evaluate the Virtual Corset's accuracy for reconstructing elevation angles from acceleration data, in static and dynamic conditions using the acceleration data from one axis and three axes.

2. Methods

The first step was to derive an equation to convert accelerometer data to elevation angles. During static positioning, the resultant acceleration detected by a tri-axial accelerometer is gravity (g). In the current study the elevation angle was defined as the angle between the z-axis of the tri-axial accelerometer and the resultant gravity vector (Fig. 1). Two approaches were selected to calculate the elevation angle. The first was with the use of data from only one accelerometer (z-axis):

$$\theta = \cos^{-1}\left(\frac{z}{g}\right) \tag{1}$$

The second was with the use of data from all three accelerometers (xyz axes). For this approach, the first step is to solve for the length a:

$$a = \sqrt{x^2 + y^2} \tag{2}$$

Next θ is given as:

$$\theta = \tan^{-1}\left(\frac{a}{z}\right) \tag{3}$$

Combining Eqs. (2) and (3) yields Eq. (4), which expresses the elevation angle as a function of the data from all three accelerometers:

$$\theta = \tan^{-1}\left(\frac{\sqrt{x^2 + y^2}}{z}\right) \tag{4}$$

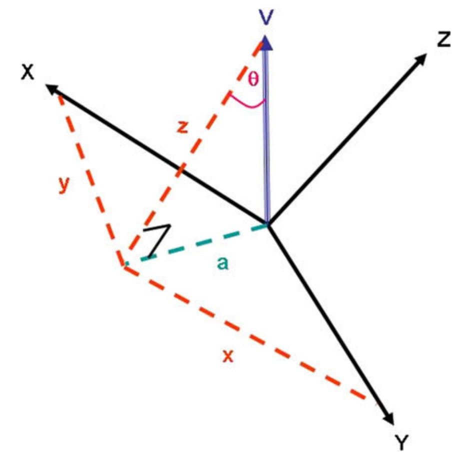

Fig. 1. Vector projection on the XY plane.

2.1. Instrumentations and calibration

The Virtual Corset (Microstrain, Inc., VT, USA) is a pager-sized (6.8 cm by 4.8 cm by 1.8 cm), battery powered tri-axial accelerometer with an integrated 2-Mb data logger, with a total weight of 72 g and no associated cables. Since this device was originally designed for use with the trunk, the standard output was the projection angles of flexion/extension and lateral bending. The manufacturer modified the internal software so that the device would save the raw data from the three accelerometers for this study. This device is constructed from two dual axis accelerometers, ADXL202E (Analog Device, MA, USA) ± 2 g and 0.2% nonlinearity, with a sampling rate of approximately 7.6 Hz. In the present study four Virtual Corsets were tested under static conditions and three were tested under dynamic conditions.

The Virtual Corset's raw data output is acceleration in bits. To convert this acceleration to g (gravitational units) each Virtual Corset was calibrated using a customized jig, which rotates around three orthogonal axes. The minimum and maximum values from the raw data for each acceleration axis were registered and used to calculate the gain and offset of each axis for the different Virtual Corsets. The gain was calculated by subtracting the minimum value from the maximum value and dividing the result by two. The offset was calculated by averaging the maximum and minimum values. Using the calculated gain and offset the raw acceleration data were converted from bits to g's Eq. (4) was then used to calculate elevation angles.

In the static testing, a PRO 3600 digital protractor (Macklanburg, OK, USA), with a reported accuracy of 0.1°, was used to validate the Virtual Corset. The Virtual Corset and the digital protractor were attached to a vise, which could rotate about three axes similar to the shoulder joint. The International Society of Biomechanics recommend a Y-X'-Y'' Euler sequence to describe humeral rotations. The first rotation (plane of elevation) describes the plane at which an arm elevation is occurring. The second rotation represents the actual arm elevation and the third rotation represents the internal/external rotation of the arm (Wu et al., 2005). In the present study only the horizontal axis (which represents humeral elevation