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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:

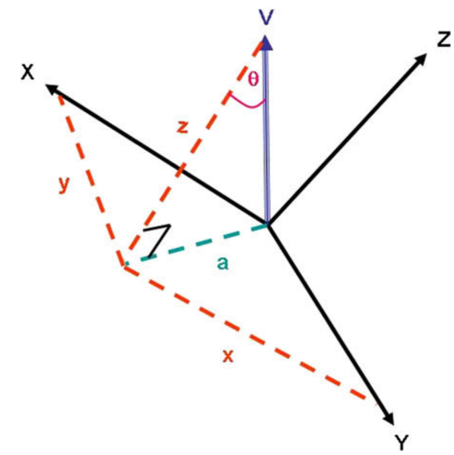

Fig. 1. Vector projection on the XY plane.

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

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 rotation) and the vertical axis (which represents humeral plane of elevation rotation) were simulated.

For dynamic testing, an SW22B Wirewound precision single turn potentiometer (ETI Systems, Inc, CA, USA), with a linearity tolerance of ±0.5%, was connected to an aluminum arm to create a pendulum. The pendulum arm dimensions were 50 × 1 × 1 cm. The Virtual Corset was attached to the pendulum arm at different distances to validate it under different dynamic conditions.

2.2. Data collection

2.2.1. Static

When measuring acceleration with a tri-axial accelerometer under static conditions the resultant vector is the gravitational acceleration, thus, Eqs. (1) and (4) can be used to calculate the elevation angle relative to gravity. To validate Eqs. (1) and (4), the Virtual Corset was mounted on a vise which could be rotated through 360° of elevation and 90° of plane of elevation (Fig. 2), where 0° of plane of elevation represents the frontal plane and 90° of plane of elevation represents the sagittal plane. The digital protractor was attached to the vise to identify the elevation angles at 0° of plane of elevation. The vise was rotated through 360° of elevation in 10° increments. At each elevation angle, the plane of elevation was varied from 0° to 90° in 15° increments. Each position was held for 10 s and the acceleration data were recorded and averaged for each axis. Elevation angles were calculated using Eqs. (1) and (4). This procedure was repeated at two different days for each Virtual Corset.

2.2.2. Dynamic

Linear accelerometers are sensitive to linear acceleration. Hence, any linear acceleration acting on the system besides gravity will result in an error of the predicted elevation angle. To predict the error in elevation angle due to linear acceleration, the angle between the actual resultant and gravity acceleration vectors was calculated. If these two vectors are the same, then the angle should be zero. The cross-product equation was used to find the angle between the two vectors.

To calculate the predicted angle error in a controlled environment we used a pendulum, which introduced high and variable levels of angular velocities and accelerations. The pendulum was chosen because it was relatively close to in vivo movement of a body segment, in that it rotates around an axis (joints) with changing angular velocities and accelerations. For angular motion, the resultant linear acceleration is the sum of the gravitational ($g = -9.8\ \mathrm{m/s^2}$), radial (a_r) and tangential (a_t) acceleration vectors (Fig. 3). Radial acceleration is the product of the angular velocity squared and the radius and the tangential acceleration is the product of the angular acceleration and the radius. The error (β) due to these non-gravitational accelerations is a function of the angular position (θ), velocity (ω) and acceleration (α) and distance from the virtual corset to the axis of rotation (r):

$$\beta = \sin^{-1}\left[\frac{\alpha r\cos\theta - \omega^2 r\sin\theta}{\sqrt{(\alpha r + g\sin\theta)^2 + (\omega^2 r + g\cos\theta)^2}}\right] \tag{5}$$

To check the validity of this equation to predict the actual angle error, the Virtual Corset was mounted on the pendulum's arm at nine different distances from the pendulum's axis of rotation to the estimated center of rotation of the Virtual Corset (1 cm error) as follows: 0–10 cm in 2 cm increments and 10–25 cm in 5 cm increments. In each trial the pendulum's arm was released from an angle of −105° of elevation and data were collected from the Virtual Corset and potentiometer for 15 s and saved. The pendulum completed each cycle in approximately 1 s. The potentiometer data were sampled at 1000 Hz. These settings were repeated for each Virtual Corset at three different positions, which represent different planes of elevation, frontal, scapular (35° anterior to the frontal plane) and sagittal planes. Synchronization between the Virtual Corset and the potentiometer was achieved by searching and matching the minimum and maximum peak angles for each cycle of the Virtual Corset and the potentiometer. The actual angle error and the predicted angle error were compared.

To validate the use of the Virtual Corset beyond the pendulum setting using human movement, data of three tasks from a previous reaching study (Amasay and Karduna, submitted for publication) were used. In this reaching study the kinematic data were collected from 20 subjects at a sampling rate of 120 Hz using a Polhemus magnetic tracking system where no Virtual Corset data were collected. The data of humeral elevation were calculated relative to the global coordinate system (gravity based). In the first task subjects raised and lowered their arms a total of seven times, with each cycle lasting approximately 6 s (Constrained). Then two unconstrained reaching movements were completed: one reaching overhead (Overhead) as high as possible and one reaching to a seat belt (Belt) on the contralateral side. These data were used to

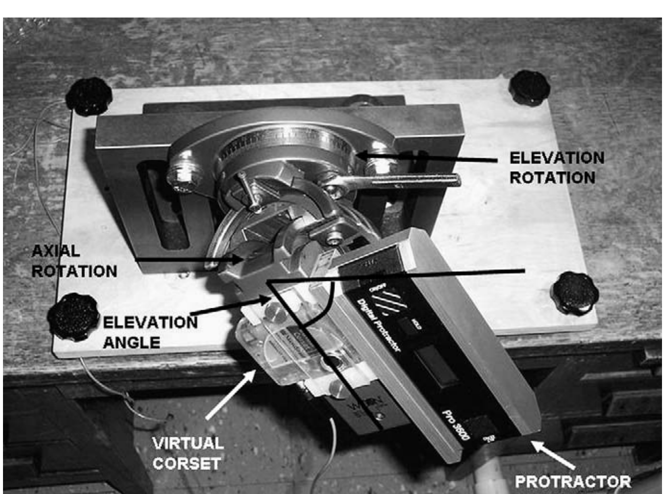

Fig. 2. Static test setup.

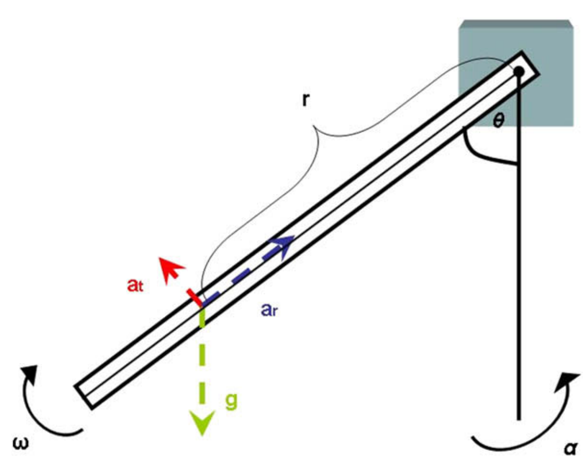

Fig. 3. Dynamic test setup.

calculate the range of predicted errors in vivo for controlled and functional movements (Eq. (5)).

2.3. Data analysis

For the static trials, root mean square (RMS) errors were calculated for each position between the known inclination angles and the calculated elevation angles using the Virtual Corset data of only one accelerometer (Eq. (1)) and of all three accelerometers (Eq. (4)). For each Virtual Corset the calculated RMS error and angle difference pattern using one axis were compared with the calculated RMS error and angle difference pattern using all three axes. Moreover, data were compared between the different Virtual Corsets and between days.

For the dynamic trials errors between the Virtual Corset calculated elevation angle and the potentiometer angle were determined for each Virtual Corset at the different locations. This error was used to validate Eq. (5). Also, the RMS and the absolute maximum predicted angle errors of the subjects were calculated and averaged for each task of the reaching study.

3. Results

For the static condition, the RMS error of the calculated elevation angles using the data from three accelerometers was found to be less than 1° in both trials for all the Virtual Corsets tested (Fig. 4). Also, the maximum difference between the calculated and the actual elevation angles was less than 2° (Fig. 5B). The calculated angle error using the data from one accelerometer showed a higher total RMS error, less than 4° (Fig. 4) with the largest differences, 14°, close to 0° and 180° of elevation (Fig. 5A). In the present study setting, the plane of elevation rotation angles did not appear to have a large influence on the error magnitude of the calculated angles; however, each Virtual Corset had its own pattern.

Under dynamic conditions the calculated elevation angle error increased as the radius increased and as the angular acceleration increased (Fig. 6). The maximum angle error difference ranged from 10° to 80° based on the radius. However, it was found that angle errors followed a similar pattern to that of the angular acceleration, in that high angle errors occurred mainly at very high angular accelerations. The calculated predicted elevation angle errors from the pendulum's data were found to be similar to the Virtual Corset calculated elevation angle errors with an RMS difference of 3° at radii of 10 cm and 25 cm (Fig. 7).

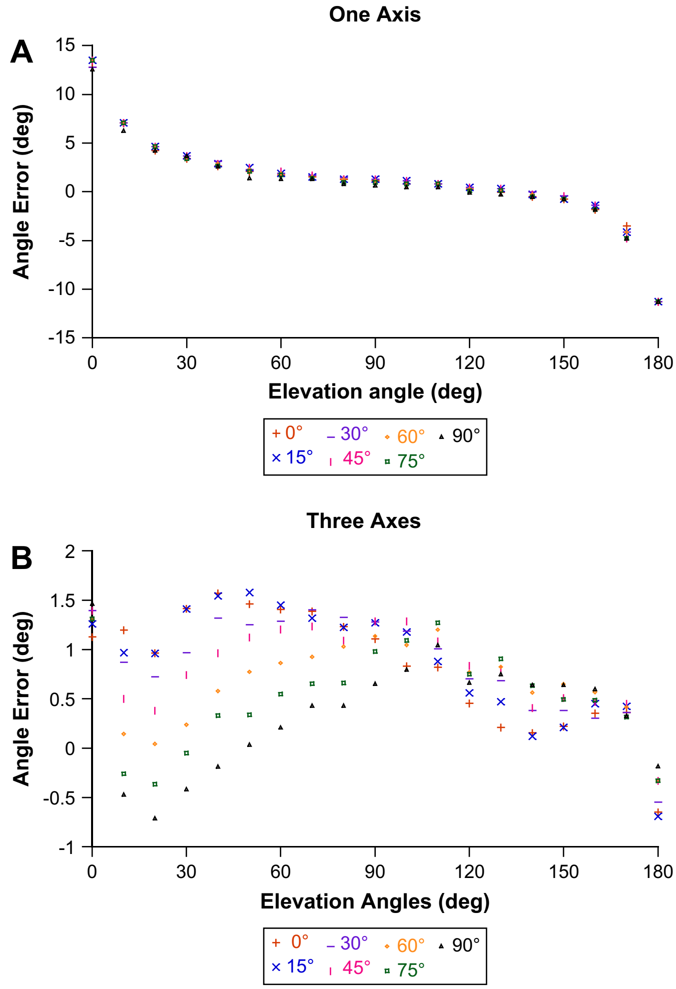

Fig. 5. Difference error of elevation angles at different planes of elevation, when using data of one axis (A) and when using data of three axes (B).

The prediction equation was used on data sets from a previously collected reaching study using a radius of 10 cm (an estimated distance of the deltoid tuberosity to the center of rotation of the humerus). Averaged RMS and absolute maximum angle error, angular velocity and angular acceleration were calculated. Comparing the in vitro (pendulum) and in vivo (reaching) data the controlled arm elevation had the lowest averaged RMS and

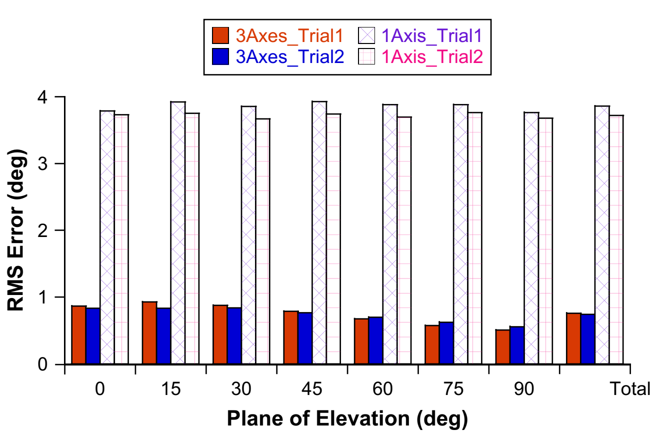

Fig. 4. Calculated RMS error of elevation angles using three axes and one axis at different planes of elevation in two different trials.

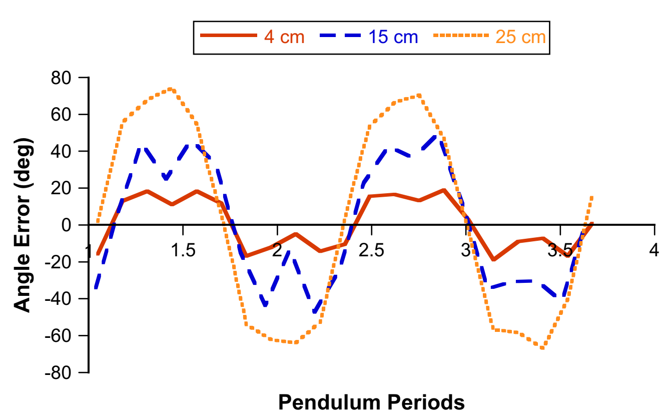

Fig. 6. Difference error between the potentiometer calculated angle and the Virtual Corset calculated angle at three different radii.

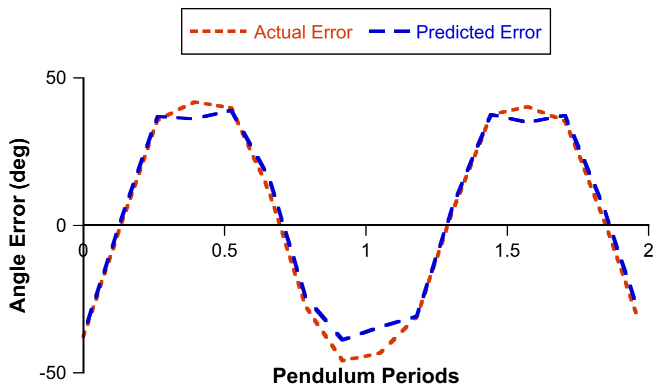

Fig. 7. Difference between the actual angle error and the predicted angle error at a radius of 20 cm.

maximum predicted angle errors. In all cases the angular velocity was lower in the reaching data by at least 190°/s; however, maximum angular acceleration was higher during the Overhead task (Table 1).

4. Discussion

The Virtual Corset was originally designed to measure upper trunk orientation relative to the line of gravity describing it by using two projection angles, flexion/extension and lateral bending. The manufacturer (Microstrain, Inc.) reports a typical accuracy of ±0.5°; however; this error is associated with a motion range of ±180° of trunk flexion and ±70° of trunk lateral bending. This specific range might be suitable for the measurement of upper trunk motion but not for the shoulder joint. The shoulder is the most mobile joint in the body, not limited to two planes of elevation. Therefore, the manufacturer customized the Virtual Corset output based on our needs to collect acceleration data, which then were converted to predict elevation angles relative to gravity. Our findings show that the Virtual Corset can be used to accurately predict arm elevation angles under static conditions. However, under dynamic conditions, researchers must understand the linear accelerations involved with the motions being studied and the placement of the Virtual Corset relative to the center of rotation of the joint.

4.1. Static conditions

Hansson et al. (2001a) reported a mean angular error of 1.3° under static conditions which is close to what we have found in this study with RMS error of less than 1°. The RMS angle error was lower using the acceleration data of the three acceleration axes to predict the elevation angle relative to the use of one axis of acceleration. Maximum angle error occurred at different elevation angles for the different Virtual Corsets when using the data of the three accelerometers; however, when using the data of one accelerometer for the different Virtual Corsets the maximum error was repeatedly at 0° and 180° of elevation angles. Moreover, it was found that the plane of elevation had little influence on the angle error. Therefore, the use of tri-axial accelerometer is preferred, especially when measuring elevation angles between 0° and 180°. It might be reasonable to use uni-axial accelerometer to measure elevation angle when measuring shoulder exposure between 30° and 150°.

4.2. Dynamic conditions

Linear accelerometers are sensitive to linear acceleration. Under static conditions the only linear acceleration the accelerometers sense is the gravitational acceleration. However, if another linear acceleration is introduced, the resultant acceleration will no longer be gravity. In the present study, the radius and angular acceleration were found to have the largest influence on angle errors. The farther the Virtual Corset was located from the axis of rotation the higher the errors; larger radius increased the tangential and radial accelerations. The same is true for larger angular accelerations. The angular velocity did not have large impact under these settings because the radial acceleration was parallel to the gravitational acceleration vector. It was also found that plane of elevation did not increase the angle error, similar to the results found under static conditions.

From a practical point of view, elevation angle RMS errors of 10° and above might be too big and meaningless to analyze. The ability to predict the angle error in elevation angle when linear accelerations, besides gravity, are introduced to the system will help the investigator to make a decision on how appropriate is the use of a triaxial accelerometer to measure exposure in specific job environment. The proposed prediction equation (Eq. (5)) has the ability to predict the errors based on specific scenarios and hence make a decision on the appropriateness of the Virtual Corset. However, in this study there were two points in the pendulum arch that the equation could not predict the same error as the actual angle error in some cases by more than 30°. This happened close to ±90° when the pendulum changed direction, the angular acceleration was at its peak and the angular velocity was close to zero. At these points the resultant acceleration components were very small, close to zero. Consequently, small changes in the data created large differences between the predicted error and the actual calculated error.

The pendulum is a unique form of motion, which includes very high angular velocities and accelerations, which under some of the scenarios the Virtual Corset might not be usable. Although, no actual in vivo data were collected to calculate the error, the pendulum simulation is plausible as a model for in vivo motion because of the angular range of motion and variety of angular velocities and accelerations. To check the utility of the Virtual Corset in measuring human arm elevation the prediction equation was applied to previously collected in vivo data of reaching tasks. In these instances the higher angular accelerations were mainly at the

Table 1
Averaged angle error, angular velocity and acceleration at a radius of 10 cm during constrained arm elevation (Constrained), two functional tasks (Belt and Overhead) and pendulum.

	Constrained		Belt		Overhead		Pendulum	
	Max	RMS	Max	RMS	Max	RMS	Max	RMS
Angle error (°)	9	1	12	3	22	5	38	23
	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Angular Velocity (°/s)	83	41	144	54	267	106	527	299
Angular Acceleration (°/s^2)	933	112	1351	314	2892	554	2109	1556

onset of the motion. The average angular acceleration and velocities were much smaller in the reaching tasks than the pendulum. The high difference in the average angular acceleration may be related to the low sampling frequency of the Virtual Corset and the pendulum setting. In this setting the pendulum arm's velocity is the smallest at the end range, which provided more data points where the angular acceleration is the largest; hence it will bias the averaged angular acceleration. Increasing the sampling frequency might improve the accuracy of the Virtual Corset by increasing the data points collected under dynamic conditions. For the constrained motion the averaged RMS angle error was 1° and for the other two reaching tasks the averaged RMS angle error was less than 6°, and can be used to evaluate shoulder elevation in a workplace. From these data it is clear that the use of the Virtual Corset for measuring ballistic motions such as baseball pitching is not practical with a reported internal rotation peak angular velocity of 8000°/s (Werner et al., 2001) and peak angular acceleration of 25,000°/s^2 (Hirashima et al., 2007). The estimated maximum angle error for this motion would be close to 90° and the peak resultant acceleration would be close to 200 g's, which is beyond the Virtual Corset's measurement capacity of 2 g's. Nonetheless, it may be usable for measuring daily activities and occupational exposure at lower angular velocities and accelerations. Hansson et al. (2006) found the upper arm angular velocity for material picking and assembly working to be 50–200°/s. Cleaning workers had higher upper arm angular velocity compared to office workers, 100–200°/s and 30–100°/s, respectively (Hansson et al., 2001b). Cote et al. (2005) found the peak angular velocities and acceleration in the shoulder during hammering task to be 196°/s and 4149°/s^2, respectively. The estimated maximum angle error for the hammering task would be close to 40° and the peak resultant acceleration would be less than 2 g's, which is still in the range of the Virtual Corset. Estill et al. (2000) found a low linear acceleration for the upper arm in industrial workers 0.32–2.70 m/s^2. These examples are still within the measurement range of the Virtual Corset. For each task or job where data collection is needed it is advisable to use Eq. (5) to estimate errors, which will help in determining the appropriateness of the Virtual Corset for that application.

Another potential limitation of the Virtual Corset is related to the perpendicular orientation between the two dual axes accelerometer, which are used to create the tri-axial accelerometer. Any physical offset between these two accelerometers may result in an increase in angle error. Our results show low error under static conditions, which would imply good positioning of the accelerometers of the Virtual Corsets tested. Other practical considerations for the use of the Virtual Corset in occupational settings include the memory and the software launching of the device. Under the configuration utilized in the present study, the Virtual Corset is capable of collecting data for 6 h, which is less than a typical full workday. An increase in the data logger memory size would extend the time of data collection and would be more useful. A start and end switch on the device for the data collection would make the use of the Virtual Corset easier in the field and for the data analysis. Currently, the device begins collecting data from the moment the battery is placed in the unit.

Although no in vivo measurements were performed in the present study it should be noted that one of the main sources of error when using surface mounted sensors to measure humeral kinematics is skin motion artifact. Ludewig et al. (2002) found that the RMS errors for humeral plane of elevation, elevation and external rotation were 3.8°, 3.1° and 7.5°, respectively. Because the measured outcome is elevation angle, and higher skin and muscle artifact were found to occur in humeral external/internal rotation, we believe that the skin and muscle artifact of the Virtual Corset will be relatively smaller but may contribute to an increase in the reported angle errors for the Virtual Corset.

The size and weight of the device may also contribute to this artifact. As was indicated in the methods section, the Virtual Corset is less cumbersome and its size and weight are relatively small with respect to the other low cost product available in the market. With a mass of only 72 g, when placed on upper part of the humerus, the device adds less than 1% to the gravitational torque of the upper extremity.

Finally, the most mobile joint in the human body is the shoulder. The output of the Virtual Corset is the elevation angle; it cannot detect the plane of elevation of the arm. To overcome this issue new systems have been developed which incorporate tri-axial accelerometers and gyroscopes. However, these systems suffer from an increase in error as a result of the gyroscopes cumulative drift around the vertical axis and the alignment of the gyroscopes sensors to the body segments (Luinge et al., 2007).

5. Conclusions

The Virtual Corset (tri-axial accelerometer) can be used to accurately reconstruct elevation angles under static conditions. In order to improve data collection qualities under dynamic conditions the following recommendations are offered:

1. Locate the Virtual Corset as close as possible to the joint center of rotation (to reduce the radius).
2. Estimate the maximum and average angular velocity and acceleration of the task.
3. Determine the typical and maximal range of humeral elevation angle.
4. Use Eq. (5) to determine whether the expected errors are within acceptable tolerances for the given experiment.

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