A Comparison of Sensor Placement for Estimating Trunk Postures in Manual Material Handling

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Abstract. Wearable measurement systems have become increasingly more popular in estimating exposures to awkward trunk postures. One limitation in using these systems is the lack of research confirming the optimal placement of the sensors for accurate quantification of trunk postures. The present study explored the effect of sensor placement in estimating trunk postures using Xsens^{TM} (Xsens Technologies, NL) during simulated manual material handling tasks in the laboratory. The researchers found a single IMU on the sternum estimated summary measures and percent time in trunk posture categories similarly to the reference method placement.

Keywords: Low back disorders · Manual material handling · Sensors

1 Introduction

For decades, low back disorders (LBDs) have been recognized as a major cause of injury and disability among many occupational populations (NRC 2001; Marras et al. 2009). A number of systematic reviews have associated awkward postures, specifically postures of the trunk, to the development of LBDs (Andersen et al. 2007; Punnett and Wegman 2004; Putz-Anderson and Bernard 1997; Marras et al. 1995; da Costa and Vieira 2010; Jonsson 1988; Punnett et al. 1991). Certain tasks such as manual material handling (MMH) routinely demand workers to engage in movements inducing awkward trunk postures (Coenen et al. 2013; Putz-Anderson and Bernard 1997; Marras 2010). In an attempt to improve work conditions, NIOSH has called for improved exposure assessment methods, emphasizing on the importance of effectively quantifying exposure to awkward postures in MMH tasks (CDIR 2007).

Direct exposure methods have become common tools used in the quantitative analysis of estimating trunk postures magnitude, duration, and frequency. As a result of recent technological advancements, wearable measurement systems have become more portable for field application, conformable to wear, and cheaper to manufacture (Chaffin et al. 2017).

One limitation of current wearable measurement systems is the lack of knowledge on of the effects of different sensor placement on estimating trunk postures. Previous research has analyzed trunk postures using sensors located on the chest or sternum, lumbar and thoracic regions of the back, shoulders, head, and side of the trunk (Fethke

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et al. 2011; Wong et al. 2009; Faber et al. 2009; Lee et al. 2017; Driel et al. 2013; Graham et al. 2009; Schall et al. 2015a; Yan et al. 2017). No established consensus exists about optimal placement of sensors on parts of the trunk to estimate trunk postures. Estimating trunk postures in the field with wearable measurement systems is challenging because of obtrusive protective equipment preventing sensor placement, sensors being disturbed by thermal, electromagnetic, and mechanical forces, and worker anthropometrics preventing the identification of necessary body landmarks. Determining potential similarities among motion sensors placed on different regions of the trunk can improve the usability of wearable measurement systems in the field. The purpose of the present study was to assess the effect of sensor placement in estimating trunk postures using the Xsens^{TM} (Xsens Technologies, NL) three-dimensional kinematic system.

2 Methods

2.1 Participants

A convenience sample of 30 healthy participants was recruited from Colorado State University. Participants were excluded if they were under 18 years of age or reported experiencing musculoskeletal pain or injury during the time of data collection. After hearing the study protocol and requirements, participants completed and signed forms of consent and photograph release. All procedures in the study were reviewed and approved by the University Institutional Review Board.

2.2 Simulated MMH Tasks

In the lab, participants completed a MMH task which included continuously handling a 1.0 lb. (0.45 kg) cardboard box (length × width × depth = 15 in × 11 in × 2 in) on a table. Data collection began with participants standing upright in a neutral position with arms to the side and feet parallel to one another. Described and depicted in Fig. 1, participants were required to reach for, lower, raise, and push a box in one continuous motion. Participants then returned to neutral position, indicating the completion of one

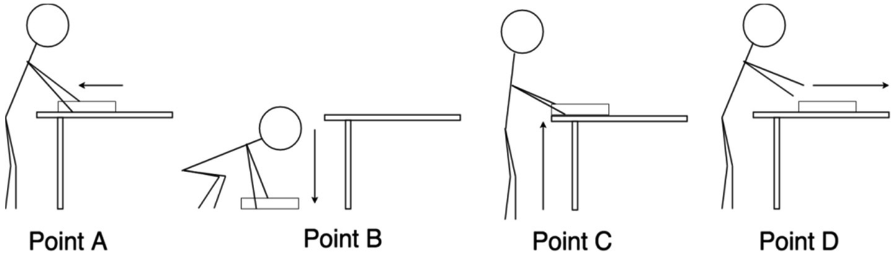

Fig. 1. The manual material handling tasks completed in the lab by each participant for 10 min (from A to D in one fluid motion). The participants started with (A) reaching for the box and pulling it towards their body (B) lowering the box to the ground without releasing it (C) lifting the box back up to the table and (D) pushing the box across the table.

MMH task cycle, and given five to six seconds of active recovery in the form of walking between MMH task cycles. The frequency of the task was self-paced with participants completing five to eight MMH task cycles per minute for a total of ten minutes.

2.3 Instrumentation

Each participant was fitted with the Xsens™ kinematic system, an inertial measurement system designed for full body and segment motion estimation. The system model used was the Xsens MVN BIOMECH Awinda which consisted of 17 inertial measurement units (IMUs) attached to body segments simultaneously using Velcro straps, a unisex spandex shirt, a headband, and two pairs of gloves (Xsens Technologies B.V. 2015). Each IMU (height × length × width = 55 mm × 40 mm × 10 mm, 16 g) contained a piezoelectric accelerometer (triaxial, ± 16 g), gyroscope (triaxial, ± 2000 deg/sec), magnetometer, and barometer (Xsens Technologies B.V. 2015). The Xsens system estimates velocity, acceleration, and position at a sampling rate of 60 Hz.

Each of the 17 IMUs were secured on the body following anatomical landmarks suggested by the manufacturer. The present study only focused on IMUs on the sternum (2 in Fig. 2), right shoulder (3 in Fig. 2), and sacrum (4 in Fig. 2) but use of additional IMUs was mandatory to execute calibration, data collection, and data processing.

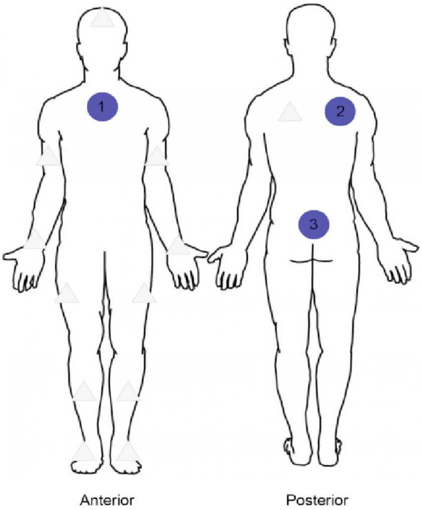

Fig. 2. Sensor placement for (1) Xsens sensor on sternum, (2) Xsens sensor on right shoulder, and (3) Xsens sensor on sacrum. Grey triangles mark Xsens sensors necessary for system operation but not used to calculate trunk posture estimates.

The Xsens system provided trunk flexion and extension estimates in the sagittal plane based on IMU motion data, Kalman filtering (Xsens Kalman Filter for Human

Movement, Xsens Technologies, NL), body dimensions for each participant, and a built-in biomechanical model. The system uses a right-hand-coordinate system meaning a positive value indicates trunk flexion whereas a negative value indicates trunk extension. Body dimensions were recorded and inputted into supplier-provided software (Xsens MVN Studio 4.0, Xsens Technologies, NL). Prior to the MMH task, the Xsens system was calibrated per manufacturer's instructions.

Estimates of trunk flexion and extension for the sternum, sacrum, and right shoulder segments were recorded in Euler angle form, downloaded in quaternion form using Xsens MVN Studio 4.0 (Xsens Technologies, NL), resampled at 10 Hz, and converted to rotation angles using Matlab (r2016b, The MathWorks Inc., Natick, MA).

Three sensor placement configurations to measure trunk flexion and extension in the sagittal plane were used: (1) the sternum segment values relative to sacrum segment values (X-SST), (2) sternum segment values only (X-ST), and (3) right shoulder segment values only (X-SH). Using trunk flexion and extension estimates derived from IMUs on the right shoulder and sternum was in accordance with manufacturer's requirements of sensor placement and with previous studies in the literature (Plamondon et al. 2007; Foerster et al. 1999; Lee et al. 2017; Fethke et al. 2011; Driel et al. 2012; Graham et al. 2009; Schall et al. 2015a; Yan et al. 2017). Using estimates from the sternum placed IMU relative to the sacrum placed IMU was used as the reference method in the present study because (1) it was a method recommended by the manufacturer and (2) it was similar to comparative studies which have shown this method to be comparable to gold-standard motion systems (i.e. optoelectronic systems) for full body and trunk motions (Roetenberg 2009; Salas et al. 2016; Schepers et al. 2010; Schall et al. 2015a; Schall et al. 2015b; Schall et al. 2016; Plamondon et al. 2007; Robert-Lachaine et al. 2016; Wong and Wong 2008; Van Driel et al. 2009; Bauer et al. 2015; Kim and Nussbaum 2013; Godwin et al. 2009).

2.4 Statistical Analysis

Ensemble averages of trunk flexion and extension estimates were created for each participant (for all sensor configurations) using a custom signal processing tool developed in Matlab (r2016b, The MathWorks Inc., Natick, MA). The arithmetic mean, peak flexion, peak extension values were calculated for the ensemble averages of each measurement method (X-SST, X-ST, and X-SH). Additionally, the 10th percentile, 50th percentile, 90th percentile, 99th percentile, and variation of trunk flexion and extension (difference between 90th and 10th percentiles) of the amplitude probability distribution function were calculated as these are common metrics in exposure assessment studies (Jonsson 1978; Schall et al. 2016; Schall et al. 2015a; Hansson et al. 2010; Lee et al. 2017; Kazmierczak et al. 2005; Schall et al. 2015b; Salas et al. 2016; Howarth et al. 2016). Another metric assessed was the participant's time spent in specific trunk posture categories for the entire ten minutes of simulated MMH task. Based on previous research, the four categories were defined as trunk flexion and extension in the sagittal plane at <0° (Category 1), 0°–30° (Category 2), 31°–60° (Category 3), and >61° (Category 4) (Marklin and Cherney 2005; Hoogendorn et al. 2000; Korshøj et al. 2014; NIOSH 2016; Villumsen et al. 2015; Coenen et al. 2013).

Pearson correlation coefficients and intraclass correlation coefficients were calculated for the mean, 10^{th}, 50^{th}, and 90^{th} percentiles, variation of trunk flexion/extension, and percent time in Category 1 through 4. For the Pearson correlation coefficients, the criteria used to evaluate the strength of linear relationship between metrics was the following: no linear relationship = 0, weak = 0.10 to 0.30, moderate = 0.30 to 0.50, and strong = 0.50 and higher (Taylor 1990). For potential agreement, estimates of ICC and their 95% confident intervals were based on a mean-rating (k = 5), absolute-agreement, two-way mixed-effects model. Agreement level was concluded using criteria by Lee et al. (1989) for the 95% confidence intervals of the ICC: ICC < 0.50 as poor agreement, 0.50 < ICC < 0.75 as moderate agreement, and ICC > 0.75 as strong agreement. Data analysis procedures were conducted using SPSS with a significance level set at 0.05 (Version 21.0, IBM Corp., USA) and graphic procedures were conducted in Excel 2017 (Version 15.36, Microsoft, USA).

3 Results

All participants were recruited from the Colorado State University in Fort Collins, Colorado, USA. The participants (n = 30) were 53% male and 47% female (mean age = 25 years, SD = 4.0; mean height = 452 cm, SD = 27.4 cm).

Estimates of trunk flexion and extension from the reference method, X-SST, and alternative measurement methods X-ST, and X-SH were used to produce ensemble averages of trunk flexion and extension (Fig. 3). The majority of ensemble averages of the participants had three primary peaks characterized by the reaching, pushing, and lowering/lifting motions, respectively, of the simulated MMH task. Ensemble averages typically ranged from approximately three to ten seconds in duration. The largest peak of trunk flexion consistently occurred though the lowering/lifting steps of the MMH task.

3.1 Trunk Flexion and Extension Summary Measures

Summary measures including the mean, peak flexion and extension, 10^{th} percentile, 50^{th} percentile, 90^{th} percentile, and variation (90^{th}–10^{th} percentile) of trunk flexion estimates from X-SH were similar to summary measures from the reference system (Table 1). Similarly, summary measures of X-ST were somewhat comparable, but values for peak flexion and extension, and 90^{th} percentile were higher than estimates from X-SST (Table 1). Pearson correlation coefficients for summary measures for X-ST and X-SH were observed to have strong correlation coefficients, ranging from 0.50 to 0.88 (Table 2). Intraclass correlation coefficients and 95% confidence intervals suggest there was a strong agreement for X-ST and X-SH in estimating trunk flexion and extension observed for the 10^{th} and 50^{th} percentile estimates (Table 3). The 90^{th}, 99^{th}, and variation estimates of trunk flexion for X-ST and X-SH have moderate agreement to the reference method (X-SST) (Table 3).

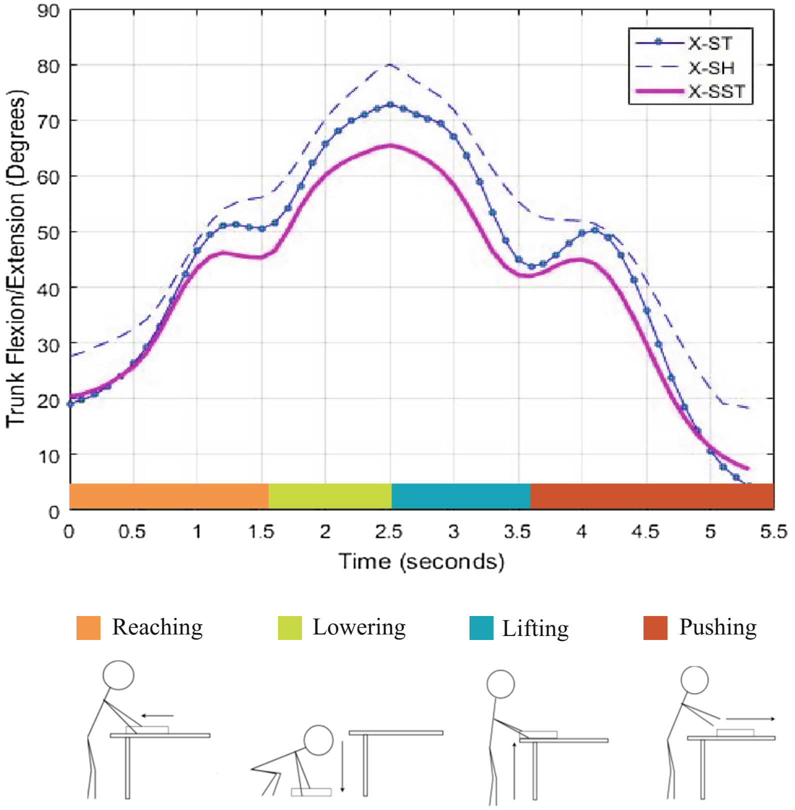

Fig. 3. Example of ensemble average of trunk flexion and extension waveform in sagittal plane by measurement method (X-SST as reference method, X-ST, and X-SH) for one participant.

Table 1. Mean (SD) of summary measures for trunk flexion/extension ensemble averages by measurement method*

Summary measure	X-SST	X-ST	X-SH
Mean (°)	32.0 (9.3)	33.1 (9.9)	30.9 (9.6)
Peak flexion (°)	60.3 (7.8)	69.3 (7.7)	64.2 (9.3)
Peak extension (°)	15.5 (9.0)	11.0 (9.0)	9.8 (9.1)
10th percentile (°)	18.8 (8.6)	14.3 (9.0)	14.3 (9.3)
50th percentile (°)	27.7 (10.3)	27.6 (12.1)	26.0 (11.5)
90th percentile (°)	54.4 (9.8)	62.8 (9.2)	57.7 (9.6)
99th percentile (°)	60.2 (7.8)	69.2 (7.7)	64.1 (9.3)
Variation (90th–10th%)	35.6 (8.3)	48.6 (10.6)	43.4 (11.6)

*X-SST = IMU on sternum relative to IMU on sacrum,
X-ST = estimates from Xsens IMU on sternum,
X-SH = estimates from Xsens IMU on right shoulder.

Table 2. Pearson correlation coefficients (r)* for the mean, 10th percentile, 50th percentile, 90th percentile, and variation of trunk flexion/extension by measurement method**

Summary measure	X-SST	X-ST	X-SH
Mean (r)	REF	0.86	0.68
10th percentile (r)	REF	0.86	0.57
50th percentile (r)	REF	0.88	0.65
90th percentile (r)	REF	0.54	0.55
Variation (90th–10th%) (r)	REF	0.56	0.50

REF = reference method

*Pearson correlation coefficients were statistically significant ($p < 0.05$) unless noted otherwise (two-tailed)

**X-SST = IMU on sternum relative to IMU on sacrum, X-ST = estimates from Xsens IMU on sternum, X-SH = estimates from Xsens IMU on right shoulder.

Table 3. Intraclass correlation coefficients (ICC) and 95% confidence intervals for 10th, 50th, and 90th percentiles and variation of trunk flexion/extension estimates between reference* and alternative methods**

	Intraclass correlation coefficient (ICC)[b]	95% confidence interval	
		Lower bound	Upper bound
10th percentile			
X-ST	0.92	0.84	0.96
X-SH	0.93	0.85	0.96
50th percentile			
X-ST	0.92	0.84	0.96
X-SH	0.78	0.55	0.89
90th percentile			
X-ST	0.70	0.37	0.85
X-SH	0.71	0.39	0.86
Variation (90th–10th%)			
X-ST	0.70	0.37	0.85
X-SH	0.63	0.24	0.82

*Reference method = X-SST, alternative methods = X-ST, X-SH

b = ICC for average measures using a consistency definition, two way mixed models effect

**X-SST = IMU on sternum relative to IMU on sacrum, X-ST = estimates from Xsens IMU on sternum, X-SH = estimates from Xsens IMU on right shoulder.

3.2 Percent Time

On average, the participants spent approximately 60% of the time in Category 2 (0°–30°), about ~20% in Category 3 (30°–60°), and the rest of the time dispersed among Category 1 (<0°) and Category 4 (>60°). Summary measures and Pearson correlation coefficients of percent time in each category by measurement method are presented in

Table 4. Strong correlation coefficients were observed between X-ST and the reference method across all four posture categories. Intraclass correlation coefficients and 95% confidence intervals of the percent time spent in each posture category are provided on Table 5. High intraclass correlation coefficients of X-ST indicated moderate agreement with the reference method in all four posture categories. Percent time estimates from X-SH were a more inconsistent with moderate agreement shown in Category 2 and 4.

Table 4. Summary measures of percent time in Category 1 to 4* per measurement method***

Summary measure	X-SST	X-ST	X-SH
Category 1			
Minimum (%)	0.0	0.0	0.0
Maximum (%)	19.6	21.1	4.6
Mean (%)	1.9	3.0	0.3
Standard Deviation (%)	4.8	5.5	0.9
Pearson correlation coefficient (r)**	REF	0.57	-0.11
Category 2			
Minimum (%)	30.7	44.4	43.8
Maximum (%)	83.8	79.1	78.6
Mean (%)	65.3	66.1	63.4
Standard deviation (%)	13.2	8.1	8.4
Pearson correlation coefficient (r)**	REF	0.60	0.60
Category 3			
Minimum (%)	11.4	7.0	9.2
Maximum (%)	56.0	42.0	43.9
Mean (%)	26.0	21.0	28.2
Standard deviation (%)	11.1	7.3	8.6
Pearson correlation coefficient (r)**	REF	0.58	0.47
Category 4			
Minimum (%)	0.0	0.2	0.0
Maximum (%)	16.8	18.4	21.8
Mean (%)	6.8	9.9	8.2
Standard deviation (%)	4.9	4.0	6.5
Pearson correlation coefficient (r)**	REF	0.50	0.51

* Percent time in Category 1 (>0°), Category 2 (0°–30°), Category 3 (30°–60°), and Category 4 ($\geq 60°$) trunk flexion/extension in sagittal plane

**Pearson correlation coefficients were statistically significant ($p < 0.05$) unless noted otherwise

*** X-SST = IMU on sternum relative to IMU on sacrum,
X-ST = estimates from Xsens IMU on sternum,
X-SH = estimates from Xsens IMU on right shoulder.

Table 5. Intraclass correlation coefficients (ICC) and 95% confidence intervals for percent time estimates in Category 1 to 4 between reference* and alternative methods**

	Intraclass correlation coefficient (ICC)^b	95% confidence interval	
		Lower bound	Upper bound
Category 1			
X-ST	0.72	0.51	0.87
X-SH	0.38	−1.27	0.49
Category 2			
X-ST	0.70	0.52	0.86
X-SH	0.71	0.59	0.86
Category 3			
X-ST	0.69	0.46	0.86
X-SH	0.63	0.52	0.82
Category 4			
X-ST	0.66	0.58	0.74
X-SH	0.65	0.57	0.74

b = ICC for average measures using a consistency definition, two way mixed models effect

*Reference method = X-SST, alternative methods = X-ST, X-SH

**X-SST = IMU on sternum relative to IMU on sacrum, X-ST = estimates from Xsens IMU on sternum, X-SH = estimates from Xsens IMU on right shoulder.

4 Discussion

The present study investigated the effect of sensor placement to estimate trunk postures by comparing an IMU on the sternum (X-ST) and an IMU on the right shoulder (X-SH) to reference method represented by an IMU on the sternum relative to an IMU on the sacrum (X-SST).

4.1 Summary Measures

The findings of the study indicated trunk posture estimates from the sternum IMU were the most comparable to the estimates derived from the IMU on the sternum relative to an IMU on the sacrum. Similar summary measures and strong associations between summary measures were observed between the two measurement methods (Tables 1 and 2). First introduced in Jonsson (1978) for exposure assessments using electromyography, percentiles of exposure from amplitude probability distribution functions have been used extensively as descriptive metrics in occupational studies of biomechanical exposures. Previous literature has shown the use of these descriptive metrics for characterizing jobs and tasks, evaluating effectiveness of interventions, assessing associations between body movements and injury/pain, and comparing exposure assessment tools (Wahlström et al. 2010; Hansson et al. 2010; Kazmierczak et al. 2005; Schall et al. 2015b; Salas et al. 2016; Howarth et al. 2016; Vasseljen and

Westgaard 1997; Bao et al. 1996; Balogh et al. 2006; Unge et al. 2007; Forsman et al. 2002; Jonker et al. 2009; Åkesson et al. 1997). Similar to the present study, other researchers comparing an IMU on the sternum to IMUs on the sternum relative to the sacrum reported comparable measurements of trunk flexion and extension between the two configurations (Schall et al. 2016; Schall et al. 2015a). Because of the strong associations between summary measures, a single IMU placed on the sternum could potentially be used to estimate 10th, 50th, 90th, 99th percentiles, and variation of trunk flexion.

The findings of the study revealed the shoulder IMU was not as comparable to the sternum IMU relative to sacrum IMU. Differences between the methods were the greatest when participants experienced extreme trunk flexion and extension (Table 1). These discrepancies could be due to possible movement artifact from the Xsens shirt, scapular movement, and shoulder posture. Similar to sternum IMU, shoulder IMU estimates for the key percentiles and percent time metrics showed to have acceptable agreement in low flexion variables (10th and 50th percentiles) with estimates from the IMU on the sternum relative to an IMU on the sacrum.

4.2 Percent Time

Assessing time in posture categories has been shown to be practical in a number of industries including manufacturing, nursing, retail, forestry work, military, construction, among others (Wai et al. 2010). The IMU on the sternum showed moderate agreement in measuring time spent in the four different trunk posture categories indicating potential use as a measurement for trunk postures with this system. Similar to sternum IMU, shoulder IMU estimates of percent time metrics showed to have acceptable agreement with estimates from the IMU on the sternum relative to an IMU on the sacrum. Agreement mostly in the time spent in Category 2 (0°–30°), Category 3 (31°–60°), Category 4 (>61°) (Tables 4 and 5). Overall, the sternum IMU had more consistent agreement in estimating the percent of time in each category.

4.3 Limitations

Although the Xsens system has been tested against ‘gold-standard’ systems for posture analysis, there is not enough consensus in the literature to consider it a ‘gold standard’ system. Furthermore, the present study was comparing IMUs within the Xsens system in their ability to measure trunk flexion and extension in the sagittal plane for simulated MMH tasks. The system relies on filtering and a biomechanical model, and one cannot generate a full body representation of a participant without using all 17 sensors. The researchers used the system as intended- including all 17 sensors. Although, other research has compared a single IMU on the sternum to an IMU on the sternum relative to an IMU on the sacrum, and reported the two configurations had comparable measurements of trunk postures (Schall et al. 2016; Schall et al. 2015a). Therefore, this suggests if only three sensors from the Xsens system were compared to a validated system (optical motion capture), the sternum IMU and the sternum IMU relative to the sacrum IMU would perform similarly.

Another limitation within the present experiment was the sagittal plane was the only plane analyzed (in terms of trunk flexion and extension). The investigators hypothesize with more complex movements (involving twisting and lateral bending) might require more than a single sensor to produce reliability comparable to the present experiment.

4.4 Implications and Conclusions

Wearable measurement systems, like Xsens, are designed to estimate kinematics based off of sensor placement on anatomical landmarks on the body. The ability to place a single inertial sensor on the sternum or shoulder could serve as an alternative to estimate trunk posture when placing sensors on the sacrum and sternum is not feasible (i.e. in industries such as construction where bulky tool belts, oxygen tanks, and back belts cover parts of the trunk). In situations where worker anthropometrics (e.g. weight, size) make it difficult to locate certain landmarks or are more prone to movement artifact from skin, muscles, or other tissues, having the option to place an inertial sensor on other landmarks can also help assure quality data in exposure assessments (Sazonov et al. 2011; Gemperle et al. 1998; Feito et al. 2011).

The Xsens system requires background knowledge of biomechanics, placement of multiple sensors on different anatomical landmarks, and knowledge of data management and extraction. The complexity of Xsens could discourage occupational safety and health practitioners from adapting them in field applications. Estimating trunk postures with the sternum IMU relative to the sacrum IMU (reference method in the present study) requires a little more data processing than just a single IMU at the sternum. The results of the present study demonstrate the sternum IMU has the capability to measure summary metrics and percent time in posture categories comparable to the reference method which could simplify quantifying trunk posture exposures for occupational professionals.

Future research should include testing wearable devices in a number of simulated and field-based tasks, on workers across different industries, and against properly validated systems. Wearable measurements systems are entering the market quickly, but lacking sufficient research to support their use in daily health and safety practices. The present study adds knowledge on the agreement of estimating trunk postures summary measures and percent time with a single IMU in comparison to an IMU on the sternum relative to an IMU on the sacrum.

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