HHS Public Access
Author manuscript
*Proc Hum Factors Ergon Soc Annu Meet*. Author manuscript; available in PMC 2017 December 22.

Published in final edited form as:
*Proc Hum Factors Ergon Soc Annu Meet*. 2016 September ; 60(1): 970–974. doi:10.1177/1541931213601224.

# Comparative Analysis of Inertial Sensor to Optical Motion Capture System Performance in Push-Pull Exertion Postures

**Sol Lim**, **Andrea Case**, and **Clive D'Souza**
Center for Ergonomics, Department of Industrial and Operations Engineering, University of Michigan, Ann Arbor

## Abstract

This study examined interactions between inertial sensor (IS) performance and physical task demand on posture kinematics in a two-handed force exertion task. Fifteen male individuals participated in a laboratory experiment that involved exerting a two-handed isometric horizontal force on an instrumented height-adjustable handle. Physical task demand was operationalized by manipulating vertical handle height, target force magnitude, and force direction. These factors were hypothesized to influence average estimates of torso flexion angle measured using inertial sensors and an optical motion capture (MC) system, as well as the root mean squared errors (RMSE) between instrumentation computed over a 3s interval of the force exertion task. Results indicate that lower handle heights and higher target force levels were associated with increased torso and pelvic flexion in both, push and pull exertions. Torso flexion angle estimates obtained from IS and MC did not differ significantly. However, RMSE increased with target force intensity suggesting potential interactive effects between measurement error and physical task demand.

## INTRODUCTION

Prolonged work in awkward constrained postures and high force exertions are known risk factors for musculoskeletal disorders in manual work settings (da Costa & Vieira, 2010). Overexertion injuries have been associated with repeated and long term bending and twisting of trunk at the waist (NIOSH, 2009). Estimating the physical workload experienced by workers in the workplace necessitates reliable and accurate methods to measure worker postures and work intensities in situ.

Low-cost, wearable inertial sensors (IS) provide a useful tool for quantifying postures and physical exposures in field settings. These small and inexpensive sensors comprising of integrated accelerometers, gyroscopes and magnetometers have been used in various domains such as gait analysis (Charry et al., 2009) and activity monitoring (Oshima et al., 2011; Ravi et al., 2005).

Prior studies have investigated the accuracy of IS compared to optoelectronic motion capture (MC) systems (e.g., Faber et al., 2013; Godwin et al., 2009; Cutti et al., 2008). These studies have largely considered measurement differences to be independent of body posture, which is a function of worker anthropometry and physical task demand. A systematic investigation of IS performance as a function of occupationally-relevant task variables and task demands is a necessary step towards determining task conditions in which IS might outperform or underperform relative to conventional lab-based instrumentation methods.

We conducted a laboratory experiment to compare the performance of a low-cost IS to a conventional MC system in simulated static and dynamic work tasks under levels of physical task demand. Preliminary analysis and findings of the two-handed isometric pushing and pulling tasks are presented here.

The specific study aim was to quantify differences in IS and MC estimates of torso and pelvis kinematics relative to levels of physical task demand in a two-handed isometric horizontal hand force exertion task. Task demand was operationalized by the magnitude (intensity), direction and height of force application. We hypothesized torso and pelvic flexion to change systematically between task demands but not between instrumentation methods (IS vs. MC as reference).

# METHODS

## Study Participants

The study recruited fifteen healthy right-handed males (18–35 years old) from the university population. Age and gender restriction were applied to minimize variability in self-selected task postures. Data from three participants were excluded from the analysis due to instrument error. The resultant sample ($n$ = 12) had a mean (SD) age of 24.21 (3.98) years, height of 176.52 (4.57) cm, and weight of 69.79 (9.0) kg. Participants provided written informed consent prior to study participation and were screened for pre-existing back injuries or chronic pain using a questionnaire. The study was approved by the University's Health Sciences and Behavioral Sciences Institutional Review Board.

## Experiment Procedure

A laboratory experiment was conducted that involved participants exerting a two-handed isometric horizontal force on a height-adjustable handle instrumented with a 6-axis load cell. Participants exerted a hand force to match and maintain a required target force level (±5%) for a continuous 3s interval in 18 counterbalanced tasks conditions (Table 1) characterized by vertical handle height (at the hip, mid-point, and shoulder height), force intensity (low, medium, and high), and force direction (push vs. pull).

Target force levels were normalized to each participant and set proportional to their maximum voluntary exertion (MVE) force in a two-handed push with the handle at hip height. The MVE was measured at the start of the experiment. Participants received verbal instructions to ramp up their force exertion to a maximum over 2s interval and maintain it for a 3s interval (Stobbe, 1982). The average of two repetitions was recorded as the MVE. The resultant study sample had a hip height of 100.6 (3.59) cm. and a push MVE of 455.98 (126.05) N.

For the experiment trials, participants stood with their feet positioned in a split stance with the dominant foot leading and placed within 50 cm from the handle. Participants were free to self-select the non-dominant foot position in each task trial. A digital display monitor located anteriorly at eye level provided real-time feedback of the exerted force and target force range with a 3s countdown clock, and was reset for each task condition. Failure to produce a sustained force level within the target range for a continuous 3s resulted in the clock being reset and the trial repeated.

## Instrumentation

Measurement instrumentation comprised of a commercial data-logging IS devices (YEI Technology, Inc.) and a passive optical MC system (Qualisys Inc.). Two sensors were used in this analysis and were attached using Velcro straps to the participant's torso at sixth thoracic (T6) vertebra for tracking 3D orientations of the upper torso, and at the low-back (L5/S1) for measuring pelvic orientation. Figure 1 (left panel) shows the anatomical locations for the IS and MC markers. MC marker triads attached to the IS devices were used to track participant movements during the experiment trials. Additional MC markers attached to the participant's acromion process, cervicale (C7) and hip (greater trochanter) were used in a static reference pose (T-pose) measurement to map the marker triads to the upper torso and pelvis segment orientations.

## Data Processing

During the experiment, the IS devices recorded triaxial accelerometer, gyroscope, and magnetometer data at 100 Hz sampling frequency. MC data was collected at a sampling frequency of 50-Hz. Both IS and MC data were filtered using a second-order low-pass zero-lag Butterworth filter with a 6-Hz cut-off frequency. MC data were then up-sampled to 100-Hz and synchronized with the IS data. Three dimensional segment orientations using IS data (roll and pitch were used in this analysis) were computed using a custom algorithm implemented in MATLAB.

## Dependent Variables

Dependent measures comprised of the posture variables, torso flexion (TF, '$\theta$') and pelvis flexion (PF, '$\phi$') angles, calculated separately from the IS and MC data for each trial. In interest of brevity we have limited our analysis to torso flexion. The following values were computed:

- **i.** Mean flexion angles over the 3s task duration
- **ii.** Standard deviations (SD) over the 3s task duration
- **iii.** Root mean squared errors (RMSE) between IS and MC for the 3s task duration.

## Data Analysis

Hierarchical mixed effects models (Snijder and Bosker, 2002) implemented using SPSS v. 23 (IBM Inc.) were used to analyze the effects of within-subject task variables, viz., handle height (hip, mid, shoulder), force intensity (low, mid, high) and force direction (push vs. pull) and between instrumentation (IS vs. MC) on TF. Two different models were used to evaluate measurement error across instrumentation (IS vs. MC). The first model investigated difference in mean TF angles by task variables and instrumentation. The second model investigated for differences in RMSE by task variables. A 0.05 nominal significance level was used in the analyses. All main and two-way interaction terms were included in the analysis. Post hoc paired comparisons of significant terms ($p < 0.05$) used the Bonferroni adjustment.

# RESULTS

Table 2 summarizes the mean (SD) angle values for TF by instrumentation and the mean (SD) RMSE values between instrumentation stratified by task variables. Overall trends in mean TF values show that lower handle heights and higher target force levels are associated with an increase in TF. On average, TF was greater in push compared pull exertions.

Overall, the RMSE between IS and MC for 3s of TF ranged between 1.80 – 3.69 degrees (Table 2). RMSE during the 3s task duration tended to increase with lower handle height, higher force intensity, and push task variables.

## Analysis of Mean TF Angle

Mixed effects analysis of TF angles (Table 3) showed no significant effect of instrumentation (IS vs. MC) on the 3s-averaged TF values. This result suggests that when averaged over 3s, IS and MC provided TF angles estimates that were consistent and independent of task variables.

Significant influences of handle height, force intensity, force direction, and an interaction between force intensity and direction were observed (Table 3). Post-hoc tests showed significantly greater TF angles at lower handle heights, viz., shoulder to mid handle height: $t = -10.01$, $p < 0.001$, shoulder to hip height: $t = -28.83$, $p < 0.001$, and mid to hip height: $t = -18.74$, $p < 0.001$.

Force intensity (high-mid: $t = 4.05$, $p < 0.001$, high-low: $t = 8.78$, $p < 0.001$, med-low: $t = 4.66$, $p < 0.001$) and force direction (push vs. pull: $t = 8.03$, $p < 0.001$) were the significant factors, implying significantly greater TF with increasing force intensity also when pushing.

## Analysis of TF Angle RMSE

Mixed-effects analysis of RMSE between IS vs. MC estimates of TF angles showed significant effect of handle height, force intensity, and force direction (Table 4). No interactions between factors were observed. Post-hoc tests showed significant increase in RMSE for handle heights at the hip vs. shoulder ($t = 7.25$, $p < 0.001$), high vs. mid force intensity levels ($t = 3.56$, $p < 0.001$), and in push vs. pull force exertions ($t = 2.18$, $p = 0.031$).

# DISCUSSION

This study examined interactions between inertial sensor performance and physical task demand on posture kinematics in a hand force exertion task. Findings demonstrate a systematic influence of physical task demands on torso flexion.

Regarding the performance of IS, no significant difference between IS and MC angle estimates were observed when posture variables were averaged over the task duration.

However, comparisons of RMSE during the exertion task by condition indicated greater error magnitudes in conditions representing higher force intensity, lower handle heights, and in push exertions. While the output force was relatively isometric (target ± 5%), it is likely that body posture, specifically TF did vary during the 3s task duration, either volitionally or due to tremor in conditions of high force intensity (75% MVE). Differences in the response characteristics of IS compared to optical motion capture in recording such movements may have contributed to greater RMSE.

Further, the accuracy of IS when measuring changes in three dimensional angles has some limitations, namely, fluctuation from accelerometer and drift errors in gyroscope–based measurements (Welch & Foxlin, 2002). Godwin et al. (2009) reported RMSE in IS vs. MC estimates ranging between 3 and 15 degrees when studying human arm reaching movement, compared to a RMSE of 3.5 degrees in simple dynamic pendulum movements.

Our preliminary study suggests that inertial sensor measurement errors differ based on specific posture angles being compared (which is a function of worker anthropometry and physical task demands) and the choice of data aggregation method (i.e., whether the data is being averaged or not). Similar angle estimates were obtained when averaged over the task duration, though the variability in measurements across conditions differed.

The present study was limited to isometric two-handed exertions. Ongoing work to include additional body segments and dynamic work tasks will help provide a more comprehensive understanding of IS performance for ergonomic analysis.

## Acknowledgments

This study was supported by a pilot grant to the first author by the U-M Center for Occupational Health and Safety Engineering (COHSE) through the training grant T42-OH008455 from the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

## References

Chaffin DB, Andres RO, Garg A. Volitional postures during maximal push/pull exertions in the sagittal plane. Human Factors: The Journal of the Human Factors and Ergonomics Society. 1983; 25(5): 541–550.

Charry, E., Lai, DT., Begg, RK., Palaniswami, M. A study on band-pass filtering for calculating foot displacements from accelerometer and gyroscope sensors. Conference proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Conference (No. 2009; 2009 Jan. p. 4824-4826.

Cutti AG, Giovanardi A, Rocchi L, Davalli A, Sacchetti R. Ambulatory measurement of shoulder and elbow kinematics through inertial and magnetic sensors. Medical & biological engineering & computing. 2008; 46(2):169–178. [PubMed: 18087742]

da Costa BR, Vieira ER. Risk factors for work-related musculoskeletal disorders: a systematic review of recent longitudinal studies. American journal of industrial medicine. 2010; 53(3):285–323. [PubMed: 19753591]

Duffy VG. A methodology for assessing industrial workstations using optical motion capture integrated with digital human models. Occupational Ergonomics. 2007; 7(1):11–25.

Godwin A, Agnew M, Stevenson J. Accuracy of inertial motion sensors in static, quasistatic, and complex dynamic motion. Journal of biomechanical engineering. 2009; 131(11):114501. [PubMed: 20353265]

Granata KP, Lee PE, Franklin TC. Co-contraction recruitment and spinal load during isometric trunk flexion and extension. Clinical Biomechanics. 2005; 20(10):1029–1037. [PubMed: 16154249]

Neumann WP, Wells RP, Norman RW, Kerr MS, Frank J, Shannon HS, Groupd OW. Trunk posture: reliability, accuracy, and risk estimates for low back pain from a video based assessment method. International journal of industrial ergonomics. 2001; 28(6):355–365.

Oshima Y, Kawaguchi K, Tanaka S, Ohkawara K, Hikihara Y, Ishikawa-Takata K, Tabata I. Classifying household and locomotive activities using a triaxial accelerometer. Gait & posture. 2010; 31(3): 370–374. [PubMed: 20138524]

Ravi N, Dandekar N, Mysore P, Littman ML. Activity recognition from accelerometer data. AAAI. 2005 Jul.5:1541–1546.

Ray SJ, Teizer J. Real-time construction worker posture analysis for ergonomics training. Advanced Engineering Informatics. 2012; 26(2):439–455.

Stobbe TJ. The development of a practical strength testing program for industry. 1982

Williamson R, Andrews BJ. Detecting absolute human knee angle and angular velocity using accelerometers and rate gyroscopes. Medical and Biological Engineering and Computing. 2001; 39(3):294–302. [PubMed: 11465883]

Welch, G., Foxlin, E. IEEE Computer graphics and Applications. 2002. Motion tracking survey; p. 24-38.

Wong WY, Wong MS. Trunk posture monitoring with inertial sensors. European Spine Journal. 2008; 17(5):743–753. [PubMed: 18196296]

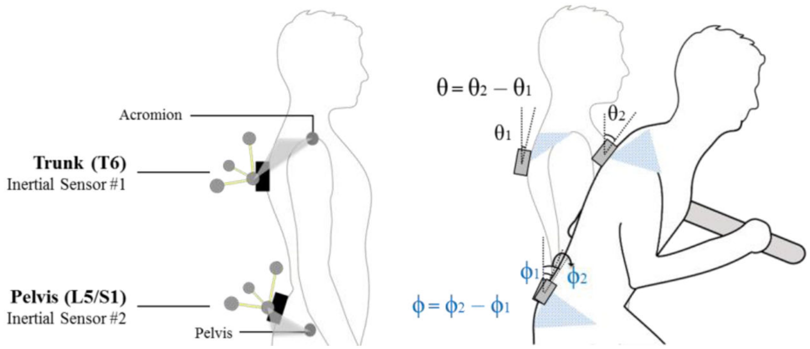


**Figure 1.**

Experimental setup (left) showing anatomical reference location for the inertial sensors (rectangles, 2 nos.) and optical MC marker triads (circles) located at the upper torso (T6) and pelvis (L5/S1). MC markers at the acromion process, cervicale (C7) and hip were used in a static pose measurement to map the marker triads to the upper torso and pelvis segment orientations. During the task trials, posture variables (right panel) comprising torso flexion 'θ' and pelvis flexion 'ϕ' angles were calculated relative to the upright standing posture for each instrumentation system.

## Table 1

Target force intensity levels for the two-handed push and pull task presented as a percentage of two-handed maximum push exertion force measured at hip height. Pull vs. push ratio was determined using reference MVE values provided by Chaffin & Andres (1983).

| Handle Height | Force Intensity | Force Direction and Magnitude % | |
|---|---|---|---|
| | | Push | Pull |
| Shoulder | Low | 19.2 | 15.9 |
| | Medium | 38.5 | 31.7 |
| | High | 57.7 | 47.6 |
| Mid | Low | 21.7 | 17.9 |
| | Medium | 43.5 | 35.9 |
| | High | 65.2 | 53.8 |
| Hip | Low | 25.0 | 20.6 |
| | Medium | 50.0 | 41.3 |
| | High | 75.0 | 61.9 |

x 83 % (Push → Pull); x 87 % (Hip → Mid); x 77 % (Hip → Shoulder)

## Table 2

Mean (SD) values for torso flexion angle (degrees) over the 3s task duration derived from Motion Capture (MC) and Inertial sensors (IS) stratified by task variables, along with the root mean squared errors (RMSE mean and SD) between MC and IS.

| Handle Height | Force Intensity | Force Direction | | | | | |
|---|---|---|---|---|---|---|---|
| | | Push | | | Pull | | |
| | | Mean (SD) | | RMSE (SD) MC vs. IS | Mean (SD) | | RMSE (SD) MC vs. IS |
| | | MC | IS | | MC | IS | |
| Shoulder | Low | 14.47 (6.13) | 14.19 (5.55) | 1.94 (2.38) | 8.60 (7.84) | 8.85 (7.12) | 1.85 (2.36) |
| | Medium | 18.07 (7.70) | 17.37 (7.27) | 2.19 (2.41) | 7.55 (7.76) | 7.94 (7.21) | 1.89 (2.45) |
| | High | 18.66 (8.43) | 18.49 (7.98) | 2.13 (2.41) | 16.73 (13.55) | 16.50 (12.30) | 2.26 (2.48) |
| Mid | Low | 22.93 (6.06) | 22.17 (6.0) | 2.22 (2.41) | 13.37 (10.63) | 13.39 (10.19) | 1.80 (2.33) |
| | Medium | 26.19 (6.14) | 25.36 (6.0) | 2.38 (2.35) | 21.80 (12.02) | 20.69 (11.17) | 2.02 (2.55) |
| | High | 26.93 (6.70) | 26.37 (6.33) | 2.49 (2.20) | 25.88 (14.85) | 24.66 (14.49) | 2.23 (2.25) |
| Hip | Low | 39.90 (10.28) | 38.40 (10.15) | 2.63 (2.24) | 29.95 (28.58) | 28.58 (12.44) | 2.49 (2.52) |
| | Medium | 42.12 (11.30) | 40.26 (9.76) | 3.36 (2.20) | 38.62 (9.17) | 36.28 (8.40) | 3.09 (2.25) |
| | High | 44.98 (14.27) | 43.12 (13.12) | 3.69 (2.19) | 42.41 (12.43) | 40.25 (11.61) | 3.07 (2.23) |

**Table 3**

Summary results from the mixed-effects analysis of mean TF angle as a function of task variables and instrumentation.

| Source | Torso Flexion Angle |
| --- | --- |
| Intercept | $F(1, 24) = 349.05$, $p < 0.001$ * |
| Handle Height | $F(2, 404) = 427.80$, $p < 0.001$ * |
| Force Intensity | $F(2, 404) = 38.57$, $p < 0.001$ * |
| Force Direction | $F(1, 404) = 64.48$, $p < 0.001$ * |
| Instrumentation (IS vs. MC) | $F(1, 24) = 0.12$, $p = 0.738$ |
| Handle Height * Force Intensity | $F(4, 404) = 1.42$, $p = 0.225$ |
| Handle Height * Force Direction | $F(2, 404) = 0.11$, $p = 0.90$ |
| Force Intensity * Force Direction | $F(2, 404) = 7.10$, $p < 0.001$ * |
| Handle Height * Instrumentation | $F(2, 404) = 0.51$, $p = 0.60$ |
| Force Intensity * Instrumentation | $F(2, 404) = 0.046$, $p = 0.955$ |
| Force Direction * Instrumentation | $F(2, 404) = 0.013$, $p = 0.909$ |

* indicates significant effect at $p < 0.05$

Author Manuscript

Author Manuscript

Author Manuscript

**Table 4**

Summary results from the mixed-effects analysis of torso flexion RMSE as a function of task variables.

| Source | Torso Flexion RMSE |
|---|---|
| Intercept | $F(1, 12) = 16.24$, $p = 0.002$ * |
| Handle Height | $F(2, 201) = 30.63$, $p < 0.001$ * |
| Force Intensity | $F(2, 201) = 6.54$, $p = 0.002$ * |
| Force Direction | $F(1, 201) = 4.71$, $p = 0.031$ * |
| Handle Height * Force Intensity | $F(4, 201) = 0.94$, $p = 0.441$ |
| Handle Height * Force Direction | $F(2, 201) = 0.511$, $p = 0.601$ |
| Force Intensity * Force Direction | $F(2, 201) = 0.02$, $p = 0.980$ |

* indicates significant effect at $p < 0.05$