VALIDATION OF A WIRELESS SENSOR SYSTEM FOR THE ESTIMATION OF CUMULATIVE LUMBAR LOADS IN OCCUPATIONAL SETTINGS

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This study aimed to evaluate the accuracy of 3D L5/S1 moment estimates from a wearable inertial motioncapture system during manual lifting tasks. Reference L5/S1 moments were calculated using inversedynamics bottom-up and top-down laboratory models, based on the data from a measurement systemcomprising optical motion capture and force plates. Nine groups of four subjects performed tasks consistingof lifting and lowering 10 lbs. load with three different heights and asymmetry angles. As a measure ofsystem performance, the root means square errors and absolute peak errors between models werecompared. Also, repeated measures analyses of variance were calculated comparing the means and theabsolute peaks of the estimated moments. The results suggest that most of the estimates obtained from thewireless sensor system are in close correspondence when comparing the means, and more variability isobserved when comparing peak values to other models calculating estimates of L5/S1 moments.

INTRODUCTION

Mechanical loading of the spine has been identified as an important risk factor for low-back pain (Coenen et al., 2013; da Costa & Viera., 2010). Laboratory studies have investigated the effects of ergonomic interventions on spinal loading by estimating L5/S1 moments through inverse dynamic analysis (Kingma et al., 1996), employing laboratory-based instrumentation such as optical motion capture (OMC) systems, force plates (FPs), and lifting boxes instrumented with force sensors. The effects of interventions in constrained laboratory conditions might not reflect effects in practice (Faber et al., 2011). It is recommended to perform these intervention studies in the real-world environment; however, it is not feasible to utilize the above-mentioned laboratory-based instrumentation. An alternative is provided by inertial motion capture (IMC) systems, consisting of small inertial/magnetic measurement units (IMUs) measuring body segment orientations.

The current study aims to investigate if 3D L5/S1 moments can be accurately assessed by using the ambulatory measurement system consisting of an IMC system and comparing results to bottom-up and top-down laboratory models consisting of optical motion capture and force plates.

METHOD

Participants

A gender-balanced sample of 36 subjects (ages between 19 to 55 years old; mean height = 173.54 cm ± 7.5 SD; mean body mass = 72.78 kg ± 12.1 kg SD) was recruited. Participants were from the Auburn University student body and local Auburn / Opelika community. Inclusion criteria included 1) no history of physician-diagnosed MSD, injury, or surgery in the low back, 2) absence of low back pain during the previous six months, and 3) no history of a physician-diagnosed neurodegenerative disorder that may affect movement (e.g., Parkinson's disease, multiple sclerosis, among others).

Subject Preparation and Data Collection

Several anthropometric measurements were obtained, including height, weight, and the lengths and circumferences of several major body links following established guidelines (Pheasant & Haslegrave, 2006). Subjects were fitted with 17 IMU Xsens Awinda sensors (Xsens Technologies, Enschede, Netherlands). Each IMU is a small wireless, battery-powered unit that measures and stores acceleration, angular velocity, and magnetic field information. The devices were secured using a combination of elastic neoprene straps and/or hypoallergenic athletic tapes. In addition to the IMU, the participants wore small, reflective motion capture markers used as a "gold-standard" reference of body segment position. For the OMC system, the reflective markers' trajectories were recorded with sixteen cameras (Optitrack Prime 13, Natural Point, Inc), using a full body protocol. For this experiment, a total of 50 reflective markers were used. A full body Plug-In Gait marker set was used to define the reflective markers' location; 11 markers were added to the 39 basic marker set, including the inside of the knees, elbows, and ankles, top of the feet, and left and right sides of the pelvis (Figure 1). The anthropometric data was used to build a rigid link biomechanical model using the information collected from the sensors. The model was compared against the one collected from the reflective markers.

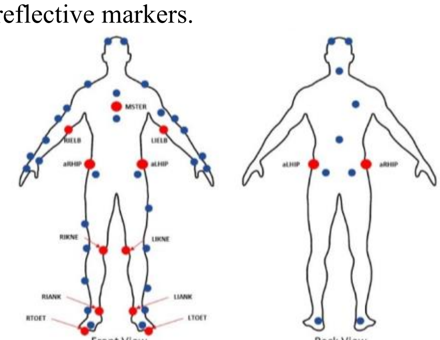

Fig 1. Adapted Plug-In Gait marker set

Systems Calibration

Before the task completion, subjects were required to perform calibrations for the OMC system and the IMC system. Segment calibration on the IMC system is necessary to align the motion trackers to the subject segments. The procedure consists of the subject holding a neutral posture for a few seconds, then walking straight forward and back to the point where they started. The OMC system was calibrated prior to the data collection session, defining the capture volume and the global coordinate system's orientation and origin.

Biomechanical Modelling

Biomechanical models employing both bottom-up and top-down approaches were used to analyze the data. A body model consisting of 15 segments (head, thorax, pelvis, hands, forearms, upper arms, upper legs, lower legs and feet) was developed on Visual3D software (C-Motion, Rockville, MD) using optical motion capture data. The position estimate for L5-S1 was defined according to guidelines (Reed et al., 1999; Dumas et al., 2007) using proportions of the anterior superior iliac spine (ASIS) distance. For the Top-Down models, the external load was assigned to both hands equally when the subject was lifting/lowering the load. Total moments were calculated for the analyses. The total moment is the vector summation of the L5/S1 moments on each plane (X, Y, Z).

Data synchronization and processing

Motion analysis was performed using the OMC and IMC systems simultaneously. OMC data was sampled at 120Hz, while IMC data was sampled at 60Hz. Force plates, OMC, and IMC data were measured synchronously using Motive™ software from Optitrack (Natural Point, Inc) as the master system. OMC signals were downsampled to 60Hz offline. Forces and kinematics were bi-directionally low-pass filtered with a second-order Butterworth filter at 6Hz for the OMC system and 5 Hz for the IMC system. Gaps in the OMC markers' trajectory were filled using cubic interpolation methods in the Motive™ software.

Experimental Procedure

Nine groups of four participants were instructed to perform different manual material handling tasks, where kinematics and kinetic data were collected. Each task included three trials with a 2-minute rest period for subjects between each trial. Subjects were instructed to lift boxes (similar to a standard milk crate) with handles consisting of a load of 10 lbs. (4.5 kg) both symmetrically and asymmetrically (i.e., 0, ±30 and ±60 degrees from sagittal) within three different heights (60 cm, 100 cm, and 140 cm). The presentation of the asymmetry angles was randomized. Heights were randomized within levels of angle, having a total of nine different combinations. The resultant combinations were labeled in the following way: AXX (Angle of 00-, 30- or 60-degrees asymmetry) and HYYY (Height of 060, 100, or 140 centimeters from the floor to the shelf). The trials are: A00_H060, A00_H100, A00_H140, A30_H060, A30_H100, A30_H140, A60_H060, A60_H100, and A60_H140.

Data Analysis

As a measure of system performance, repeated measures analyses of variance (ANOVA) were calculated comparing the means and the absolute peaks of the estimated moments. A significance level of 0.05 was used for all tests. Pairwise comparisons were performed using Tukey's test for the analysis of the means and absolute peaks, in order to identify potential significant differences between models. Root mean square error and absolute peak errors were calculated to compare the performance between systems. Statistical tests were conducted in Minitab® (version 19.2020.1, LLC, USA).

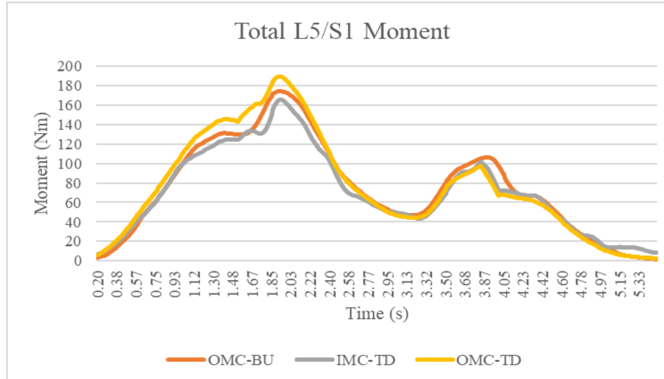

Fig 2. A typical example of the lifting task

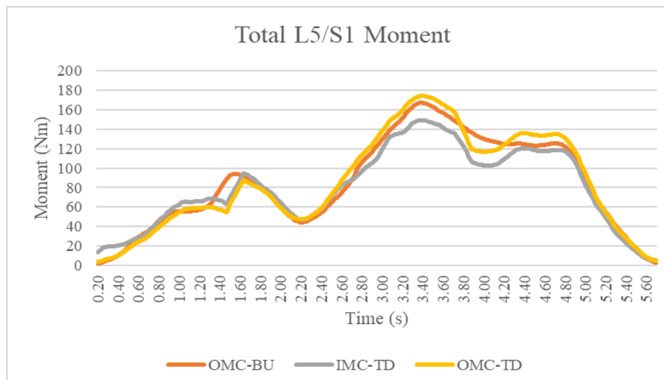

Fig 3. A typical example of the lowering task

RESULTS

Fig. 2 and Fig. 3 present typical examples of moment estimates associated with the lifting and lowering trials, showing the Bottom-Up Optical Motion Capture-based model (OMC-BU), the Top-Down Optical Motion Capture-based model (OMC-TD) and the Top-Down Inertial Motion Capture-based model (IMC-TD).

Lifting Task

Repeated measures ANOVA for the means moments showed that for all trials except A60_H060, the models did not present significant differences (Table 1). Tukey's test showed no significant differences between Models except for A60_H060, where both OMC-based models seemed to be part of one group while the IMC-based model was significantly different from these two.

The repeated measures ANOVA for the Absolute Peaks showed different results than the analysis for the means with two trials showing that the models were not significantly different (A00_H060 and A60_H100), while three trials showed trending p-values for the Models (A30_H060, A30_H140, A60_H060), all the other trials showed that the models were significantly different. Tukey's test showed mixed results, with two different trials (A00_H060 and A60_H100) not having significant differences between models. In contrast, the trials corresponding to A00_H100 and

A30_H060 presented two groups: the OMC-TD and the OMC-BU, not showing significant differences, and the other was the OMC-BU and IMC-TD not being significantly different. All the other trials presented results where both OMC-based (BU and TD) models seemed to be part of one group while the IMC-based model was significantly different from these two.

Comparing models using absolute peaks errors showed a trend where the smallest differences were observed between the OMC-TD and the OMC-BU with results between 10 Nm to 22 Nm. The larger differences were observed between the IMC-TD and the OMC-TD models, with results between 24 Nm to 40 Nm. The OMC-BU and IMC-TD difference was between the two above-mentioned presenting differences from 20 Nm to 36 Nm. Figure 4 shows the results for trial A00_H140. The RMSE followed a similar trend than the absolute peaks errors, with the OMC-TD and the OMC-BU showing lower magnitude results (between 8 Nm to 18 Nm) and the IMC-TD and the OMC-TD models showing the larger differences (between 13 Nm to 28 Nm). Again, the OMC-BU and IMC-TD difference was in the middle ground, with values from 12 Nm to 20 Nm. Figure 5 shows the results for trial A00_H140.

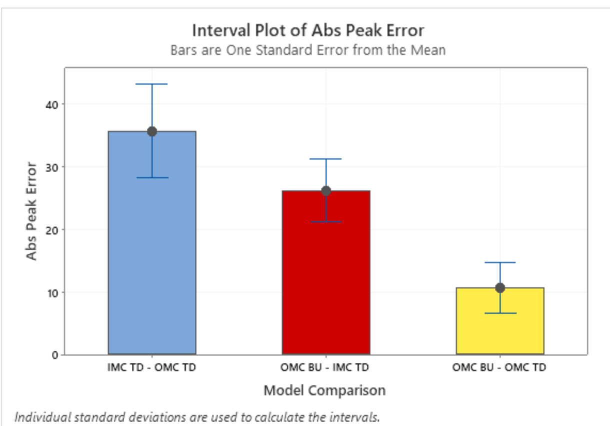

Fig 4. Absolute peak errors for lifting trial A00_H140

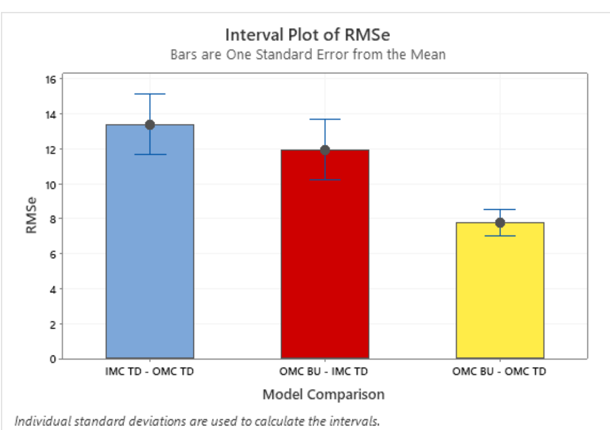

Fig 5. RMSE for lifting trial A00_H140

Lowering Task

Repeated Measures ANOVA for the means showed that for all trials except A00_H100, A00_H140, and A60_H060, the models were not significantly different (Table 2). The other trials presented trending p-values. Tukey's test showed no significant differences between Models except for A00_H100 and A60_H060, where both OMC-based models showed two groups, with one of them being the OMC-TD and the OMC-BU not showing significant differences, and the other the OMC-BU and IMC-TD not being significantly different. A60_H060 was the other exception, where both OMC-based models seemed to be part of one group while the IMC-based model was significantly different from these two.

The repeated measures ANOVA for the Absolute Peaks showed different results than the analysis for the means moments with three trials showing that the models were not significantly different (A00_H060, A30_H140, and A60_H140). In comparison, three trials presented trending p-values for the Models (A00_H100, A30_H060, and A60_H100). All the other trials showed that the models were significantly different. Tukey's test showed mixed results, with the three different trials not having significant differences between models. In contrast, the trials corresponding to A00_H100 and A60_H100 showed two groups, with one of them being the OMC-TD and the OMC-BU not showing significant differences, and the other the OMC-BU and IMC-TD not being significantly different. The rest of the trials presented results where both OMC-based models seemed to be part of one group, while the IMC-based model was significantly different from these two.

As for the Lifting task, the comparison between models using the absolute peaks errors followed a trend where the smallest differences were observed between the OMC-TD and the OMC-BU with results between 8 Nm to 23 Nm. The larger differences were observed between the IMC-TD and the OMC-TD models, with results between 20 Nm to 47 Nm. The OMC-BU and IMC-TD difference was between the two above-mentioned presenting differences from 17 Nm to 32 Nm. Figure 6 shows the results for trial A00_H140.

The RMSE followed a similar trend than the absolute peak errors, with the OMC-TD and the OMC-BU showing lower magnitude results (between 8 Nm to 21 Nm) and the IMC-TD and the OMC-TD models showing the larger differences (between 13 Nm to 24 Nm). Again, the OMC-BU and IMC-TD difference was in the middle ground, with values from 12 Nm to 20 Nm. Figure 7 shows the results for trial A00_H140.

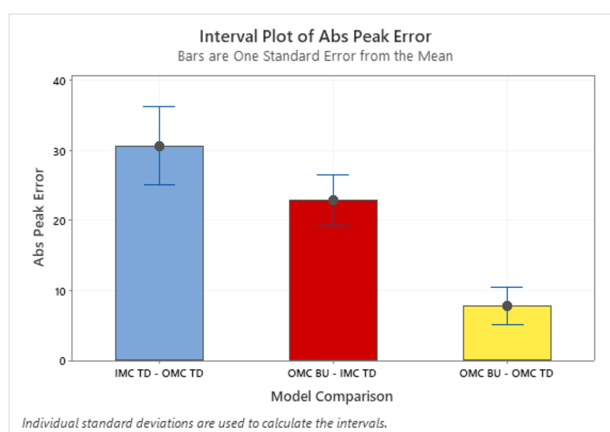

Fig 6. Absolute peak errors for lowering trial A00_H140

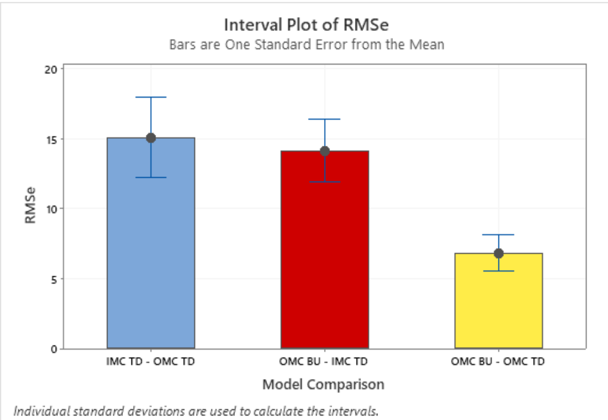

Fig 7. RMSE for lowering trial A00_H140

DISCUSSION

For the L5/S1 moments estimations, it is important to realize that the reference method or gold-standard itself has limited accuracy since the moments are not directly measured but estimated through inverse dynamics. To assess the OMC-BU model's validity as the gold-standard, OMC-BU results were compared against the OMC-TD model results. Tukey's test indicated that both OMC models were not significantly different from each other, for both the means and absolute peaks comparisons, for all trials.
The ANOVA results show that when using the mean values, the models do not show significant differences. The situation is different for the peaks, with no clear trends observed within angles or heights of lift and lowering. When comparing the means and peak values for the trials, a common scenario was that the IMC system's estimates were lower than those obtained from the OMC-based models. We have observed a similar scenario in the literature (Faber et al., 2020), and our hypothesis is related to how the segments are tracked and defined differently between systems. OMC-based models rely on real bony landmarks to determine segments' length, which might be more accurate than the IMC-based model estimates, calculated using segment orientation and some key anthropometric characteristics from the subject (height, arm span, shoulder height, hip height, among others). Additionally, differences up to 12 centimeters were observed between the estimations of the segments' length from the distal end of the hands to the proximal end of the thorax between the OMC and the IMC systems, that difference in the segments' length (lever arm) might result in lower moment estimates for the IMC model.
Another factor that might affect the variability between the Top-Down and Bottom-Up models used in this study is the thorax's definition as one rigid segment for the Top-Down calculations. In reality, the trunk is not a rigid body, so modeling the trunk as one is a potential source of error. When calculating moments from a BU approach, the Ground Reaction Forces (GRF) are the dominating factor, so the inertial properties are not as essential in the calculations; on the other hand, when estimating moments from a TD approach, the moment is mostly calculated using inertial properties. Hence, it would be expected to observe less accurate estimates when large body segments' assumptions are in place (Plamondon et al., 1996; Desjardins et al., 1998). The RMSE and absolute peak errors showed similar results to those previously observed in the literature (Faber et al., 2020: Faber et al., 2016, Koopman et al., 2018).
The degree of variability observed when estimating peak moments makes it challenging to use the system for continuous assessment. Further research is needed to understand the nature of the variability and the potential options to solve it, like a correction factor, which would make the IMU system promising for field-based risk assessment.

Limitations

One limitation of this study is the assumption of weight distribution on the hands. It is not likely that a load's weight will be evenly distributed between both sides of the body, especially when loads present irregular geometries.
Another limitation is associated with the individual characteristics of subjects. All the participants were young healthy. IMC system performance might be affected with more obese participants, where larger soft-tissue artifacts would be expected. Additionally, our group sizes were too small to include analyses on the effect of gender.
The participants were told to perform the lifting and lowering tasks with no restriction in lifting technique and speed associated with the exertion; this might affect the results' variability. Lastly, it is known that IMU sensors might experience some drift as time goes by, this was not observed during the presented work due to the short duration of the trials.

ACKNOWLEDGMENTS

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Lifting Trial		Means p-value	Tukey's Test	Abs Peaks p-value	Tukey's Test
Angle	**Height**	**Models**	**Models**	**Models**	**Models**
A00	**H060**	**0.547**	ND	**0.122**	ND
A00	**H100**	**0.105**	ND	**0.009**	OMC-TD – OMC-BU, IMC-TD – OMC-BU
A00	**H140**	**0.221**	ND	**0.002**	OMC-TD – OMC-BU, IMC-TD
A30	**H060**	**0.457**	ND	**0.013**	OMC-TD – OMC-BU, IMC-TD – OMC-BU
A30	**H100**	**0.067**	ND	**0.004**	OMC-TD – OMC-BU, IMC-TD
A30	**H140**	**0.220**	ND	**0.016**	OMC-TD – OMC-BU, IMC-TD
A60	**H060**	**0.006**	OMC-TD – OMC-BU, IMC-TD	**0.011**	OMC-TD – OMC-BU, IMC-TD
A60	**H100**	**0.357**	ND	**0.097**	ND
A60	**H140**	**0.508**	ND	**0.007**	OMC-TD – OMC-BU, IMC-TD

Table 1. Repeated-measures ANOVA results for the Lifting trial. Estimated p-values for the means and absolute peaks of the estimated moments. For the Tukey's test Results the models were separated in categories, which are ND (No differences), OMC-TD – OMC-BU, IMC-TD (one group is OMC-TD and OMC-BU, while the other Group is for the IMC-TD), and OMC-TD – OMC-BU, IMC-TD – OMC-BU (one group is OMC-TD and OMC- BU, while the other group is the IMC-TD and OMC-BU).

Lowering Trial		Means p-value	Tukey's Test	Abs Peaks p-value	Tukey's Test
Angle	**Height**	**Models**	**Models**	**Models**	**Models**
A00	**H060**	**0.487**	ND	**0.441**	ND
A00	**H100**	**0.042**	OMC-TD – OMC-BU, IMC-TD – OMC-BU	**0.031**	OMC-TD – OMC-BU, IMC-TD – OMC-BU
A00	**H140**	**0.022**	OMC-TD – OMC-BU, IMC-TD	**0.001**	OMC-TD – OMC-BU, IMC-TD
A30	**H060**	**0.322**	ND	**0.018**	OMC-TD – OMC-BU, IMC-TD
A30	**H100**	**0.063**	ND	**0.004**	OMC-TD – OMC-BU, IMC-TD
A30	**H140**	**0.213**	ND	**0.090**	ND
A60	**H060**	**0.013**	OMC-TD – OMC-BU, IMC-TD – OMC-BU	**0.004**	OMC-TD – OMC-BU, IMC-TD
A60	**H100**	**0.335**	ND	**0.046**	OMC-TD – OMC-BU, IMC-TD – OMC-BU
A60	**H140**	**0.722**	ND	**0.116**	ND

Table 2. Repeated-measures ANOVA results for the Lowering trial. Estimated p-values for the means and absolute peaks of the estimated moments. For the Tukey's test results the models were separated in categories, which are ND (No differences), OMC-TD – OMC-BU, IMC-TD (one group is OMC-TD and OMC-BU, while the other group is for the IMC-TD), and OMC-TD – OMC-BU, IMC-TD – OMC-BU (one group is OMC-TD and OMC- BU, while the other group is the IMC-TD and OMC-BU).

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