Systematic analysis of different low-pass filter cut-off frequencies on lumbar spine kinematics data and the impact on the agreement between accelerometers and an optoelectronic system

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Abstract (258 words)

A necessary step in the validation of accelerometers for the measurement of spine angles is to determine the levels of agreement with current gold standard methods. However, agreement may be a function of filtering parameters. We aimed to (1) systematically determine the effect of different filter frequency cut-offs on the peak range of motion (ROM) during forward bending as measured by accelerometers and an optoelectronic (OE) system, (2) explore the influence of filtering on agreement between systems, and (3) determine the difference in peak ROM measurement between these systems. Accelerometers and OE sensors were attached at L2, L4, and S1 of 20 asymptomatic female participants for a guided flexion trial. Signals were then iteratively low-pass filtered with cut-off frequencies ranging from 14Hz to 1Hz and peak range of motion outcome measures were compared between systems. Peak ROM was minimally affected by filter cut-off frequency for both accelerometer and OE system. The difference in peak ROM between difference cut-off frequencies were maximum 0.66^{o}, median 0.18^{o} and minimum 0.06^{o} for accelerometer derived values and maximum 0.23^{o}, median 0.08^{o} and minimum 0.03^{o} for the OE system. The maximum difference across the filtering frequencies was 0.62^{o} and the largest difference between the two systems (with outliers removed) was 0.82^{o}. Cut-off frequencies ranging from 14 to 1Hz had little effect of peak lumbar spine ROM during low velocity (6^{o}/s) forward bending, regardless of motion capture method. Filtering cut-off frequency had little effect on the differences between the accelerometer and OE system and similar measurements can be achieved using accelerometers compared to OE systems.

Introduction

Measurement of spinal sagittal motion remains of critical importance in the assessment and treatment of low back pain (Arshad et al., 2019). Currently, numerous methods exist to achieve this aim (Reddy et al., 2021; Serafino et al., 2021; Williams et al., 2013; Williams et al., 2014; Van Herp et al., 2000). However, biomechanics has seen a shift from traditional laboratory-based optoelectronic camera systems which are constrained usually to a specific environment, costly, and require line of sight, to body worn sensor systems such as accelerometers and/or inertial measurement units (Frey et al., 2020; Williams et al., 2014). Such devices are portable, cost effective, and can be worn under clothing making them attractive for clinical applications. Accelerometers in isolation can measure sagittal angle through the relationship to the vertical (i.e., gravity vector) (Frey et al., 2019; Alqhtani et al., 2016). However, raw data from accelerometers are subject to high frequency noise and filtering is a recommended step for such kinematic data (Derrick et al., 2020). A necessary step in the validation of accelerometers for the measurement of angles is to determine the levels of agreement with current gold standard methods. However, it is possible that this agreement is a function of the filtering parameters used on the data.

The decision pertaining to filtering parameters, especially cut-off frequency, often causes great discussion within and across research teams. Challenges include deciding the appropriate cut-off frequency, method to determine the appropriate cut-off frequency, and then ultimately whether to apply the same filter to a group of individuals or to take a more individualised approach to filtering. Such concern over 'getting this right' can be witnessed through criticism by journal reviewers or by conference delegates, where chosen filtering parameters are often challenged resulting in different parameters being used throughout the literature. Similar discussions over appropriate cut off frequency were held within our research group measuring sagittal range of motion of the spine and prompted this technical note. Many types of filtering are possible, but it is common in the literature to utilise a low pass Butterworth filter to remove the high frequency noise component of the signal, often associated with collecting data of human movement (Kristianslund et al., 2012). A recent review demonstrated cut off frequencies range between 1 and 15Hz (Papi et al., 2017) with 4-6Hz being commonplace in lumbar kinematics research (Bauer et al., 2015, Senington et al., 2020, Tulipani et al., 2018, Wong & Wong 2008, Alqhtani et al., 2015).

The aim of this technical note is to (1) systematically determine the effect of applying different filter frequency cut-offs on the peak range of motion (ROM) during forward bending as measured by accelerometers and an optoelectronic (OE) system respectively, (2) explore the influence of filtering on the agreement between accelerometers and an OE system, and (3) determine the difference in peak ROM measurement between accelerometers and an OE system.

Methods

Participants

Twenty asymptomatic female participants between the ages of 30 and 65 were recruited from the general population in Bournemouth, UK. Inclusion criteria included a self-reported body mass index (BMI) of less than 30 kg/m^2. Exclusion criteria included back pain that limited their normal activity for more than 1 day for the last year, a history of abdominal surgery or spondylosis, exposure to medical radiation exposure of >8mSv in the previous 2 years, and pregnancy. Questionnaires were used to confirm inclusion and exclusion criteria and written informed consent was obtained from all participants. Ethical approval was received by the National Research Ethics Service (Bristol 10/H0106/65).

Instrumentation (Accelerometers and Optoelectronic system)

Both accelerometers (ADXL335, Analog Devices, Norwood, MA, USA)) and OE sensors (Optotrack Certus Smart markers, Northern Digital Inc., Waterloo, Ontario, Canada) were attached to the skin overlying the spinous processes of L2, L4, and S1 vertebrae. The sensors were applied using double-sided (Scotch, 3M, St. Paul, MN, USA.) and medical grade cloth tape (Hypafix®, BSN Medical – Figure 1). The accelerometers were fixed in the +y down and +z anterior orientation. Data were synchronized and sampled at a frequency of 60Hz with a 16-bit A/D board (Optotrak Data Acquisition Unit, Optotrak Certus, Northern Digital Inc., Waterloo, Ontario, Canada).

Angle Calculations

A custom written code in MATLAB (MATLAB r2020b, The Mathworks, Nattick, MA, USA) was used to process accelerometer data. Spine angles were calculated by calibrating sensors with respect to gravity, converting voltages to radians with respect to gravity, converting radians to absolute angles, and calculating the relative spine angles. The change in angle from upright standing for the upper lumbar spine (L2-L4), lower lumbar spine (L4-S1), and the whole lumbar spine (L2-S1) were then calculated.

Data Collection Protocol

Upon arrival, participants changed into hospital gowns and shorts. The spinous processes of the lower spine were palpated first in a prone and then an upright standing position to determine the placement of the skin-based sensors. Next, accelerometers and OE sensors were attached and digitized according to Table 1. Participants then completed a standardized, guided flexion trial as previously described in the literature (Breen et al., 2012). In brief, participants were asked to stand on a platform and their pelvis was constrained by securing a belt around the participants' hips pushing the sacrum onto a bracing pad, thus, constraining hip motion. Participants were asked to fold their arms (left over right) over an armrest which guided them through the motion at 6°/s. The flexion trial involved 60° trunk flexion from an upright standing position and return. Following the motion trials, participants were de-instrumented and free to leave.

Data analysis & Statistics

All analysis was completed in MATLAB (MATLAB r2020b, The Mathworks, Nattick, MA, USA) Time-varying data representing the sagittal angle across time for both systems were iteratively low-pass filtered with a zero-lag, 4^{th} order bidirectional Butterworth filter with cut-off frequencies ranging from 14Hz to 1Hz. From this filtered data, peak ROM of the upper, lower, and whole lumbar spine were calculated for each cut-off frequency, for both systems respectively. To explore the effect of different cut-off frequencies the range (maximum difference in peak ROM values across the different cut-off frequencies), mean and 95% confidence interval (95%CI) of peak ROM values were calculated. To explore the influence of filtering on agreement between the two systems, the difference in peak ROM values was calculated and compared for each of the filter cut-off frequencies. The similarity of the data for the two systems were compared by assessing the differences in peak ROM (mean and 95% Confidence Intervals (CI)) and pairwise correlation.

Results

Effect of filtering on ROM

Peak ROM was minimally affected by filter cut-off frequency for both accelerometer and OE system (one participant example Figure 2 & 3, Table 2). Overall, the largest difference in peak ROM was 0.66° (median 0.18°; minimum 0.06°) across all filtering cut-off frequencies for accelerometer derived values and 0.23° (median 0.08°; minimum 0.03°) for the OE system.

Effect of filtering on agreement

Differences between the systems were minimally affected by filter cut-off frequency. Maximum peak ROM differences across the filtering frequencies was 0.62°.

Level of agreement between the 2 systems

The level of agreement between the two systems can be seen in table 3. Two individuals were large outliers for the comparisons between the systems with >20° difference. One data set seemed to have a problem with the L2 accelerometer, producing a relatively large ROM, whilst for the other, the OE system produced a ROM relatively larger than others. Such errors are most likely related to sensor attachment issues during the trial. Therefore, data are presented with these outliers both present and removed for comparison (Table 3). The largest difference between the two systems (with outliers removed) was 0.82 ° (one participant example Figure 4). This suggests that similar measurements can be achieved using accelerometers compared to OE systems. Pairwise correlation revealed cut-off frequency made no difference to the relationship between the two systems (R^2: LLx 0.998-0.998, ULx 0.986-0.987, WLx 0.995-0.996).

Discussion

Discussion

This technical note set out to explore the effect of various filter cut-off frequency on lumbar spine kinematic data associated with forward bending. It demonstrated that the differing frequencies explored had little effect of the peak ROM values. This was true regardless of the measurement technology (accelerometer and OE system) or region (lower, upper, and whole) of the lumbar spine studied. In addition, different filter cut-off frequencies had no effect on the agreement between the two systems. Therefore, agreement was not a function of the filtering parameters. This means that, based on the findings of this study, studies employing differing filtering parameters, should be comparable. This is important when manipulation of filtering parameters is not available, such as in commercial processing pipelines. However, this may only be the case in the specific parameters employed in this research. For example, the velocity of forward bending was controlled by a motorised jig, functioning at 6^{o}/s. This velocity is lower than the peak velocity reported during flexion in individuals with low back pain (Williams et al., 2013) and therefore the lack of influence of filtering may be due to the low velocity employed in this study. Previously, it has been shown that increasing movement velocity results in increased error in angle estimation from accelerometers in isolation, however this was at moderate to high velocities when compared to human movement (Chen et al., 2018). This is likely the result of tangential and centripetal acceleration acting on the accelerometer (Bernmark & Wiktorin 2002). It is not clear if forward bending at greater speeds will produce similar results and future studies should seek to determine the effect of filter cut-off frequency during forward bending at different speeds.

Our tertiary aim was to explore the agreement between peak ROM measured using accelerometers compared to an OE system. Differences were not a function of filtering, as filtering had little effect on the difference of peak value. Although not an aim of this report, it was observed that for time points other than peak, filtering had little influence on agreement between the systems (Figure 2). Therefore, with designs such as the one used in the present study, researchers and clinicians can be assured that agreement (or lack of) is not due to filtering error. As mentioned above this may not be generalizable to more dynamic movement or those of high velocity. The differences between the systems were small once outliers had been removed, indicating that accelerometers can be used as a valid alternative to OE systems for the measurement of sagittal angles of the lumbar spine during slow velocity forward bending. For context, the differences between systems (0.68-0.69°) were smaller than the effects of age (mean±95%CI > 2.96±2.00°) and sex (mean±95%CI = 5.85±1.78°) (Arshad et al., 2019) and the standard error of measurement of in vivo lumbar flexion for optoelectronic systems (Mousavi et al., 2018: 7.5°) and accelerometers (Alghtani et al., 2015: UL: 1.0° and LL:1.3°). They are also similar to the standard error of the lumbar spine in standing when comparing an OE system to x-ray (Muyor et al., 2017: 0.638-0.643°).

It should be acknowledged that 2 outliers were evident in the data and this is highly likely to be due to issues of skin attachment. This error can be comprised on skin movement artifact (Kuo et al., 2008), or failure in attachment. Due to attaching both accelerometers and OE sensors for simultaneous data capture, along with using a constraining jig, it is possible that some of the sensor attachments were erroneously affected. Protocols involving detailed observing and sensor checking should form part of any spinal motion capture methodology. This would go some way to prevent erroneous data entering data sets.

Limitations of this study are that the data were collected from a single sex cohort without pain or pathology. While it is unlikely that agreement between systems and effect of filtering would be impacted by sex, pain, or pathology, generalizing these results should be done with caution. A further limitation is the relative slow velocity of the movement tested.

Due to the small differences between the systems, accelerometers appear a valid option for the measurement of low velocity, forward bending. They offer a more practical and cost-effective method, compared to OE systems, to measure sagittal angles of the whole lumbar, lower lumbar and upper lumbar spine with the caveat that our results are generalizable only to low velocity movements.

Conclusion

This study demonstrated that different filtering cut-off frequencies had little effect on peak ROM of the lumbar spine during low velocity forward bending. This was regardless of the method used to capture the motion. Furthermore, filtering cut-off frequency had little effect on the differences between the accelerometer and OE system. Differences were small between the two systems suggesting that accelerometers and OE systems may be used interchangeably to determine upper, lower, and total lumbar angles during low velocity movements.

Conflict of interest statement

The authors have no conflicts of interest to disclose.

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Table 1. Location of sensor clusters and their associated digitized bony landmarks for the optoelectronic sensors.

Sensor Cluster Name	**Sensor Cluster Location**	**Digitized Bony Landmarks**
Lumbar Spine (L2)	L2 Spinous Process	Proximal - Most lateral portion of the 12th rib bilaterally Distal - Iliac crests (top) bilaterally
Lumbar Spine (L4)	L4 Spinous Process	Proximal - Most lateral portion of the 12th rib Distal - bilaterally Iliac crests (top) bilaterally
Pelvis	S1 Spinous Process	Proximal - Iliac crests (top) bilaterally Distal - Greater trochanters bilaterally

Table 2: Range of difference across different frequency cut offs (i.e. 1Hz to 14Hz), mean of difference, 95% confidence interval of the maximal differences between peak ROM values calculated after differing filtering frequency cut offs.

Segment	**Upper**		**Lower**		**Whole Lumbar**	
System	**OE**	**Accel**	**OE**	**Accel**	**OE**	**Accel**
Range of difference (º)	0.03-0.15	0.09-0.66	0.06-0.23	0.09-0.53	0.03-0.20	0.06-0.49
Mean difference (º)	0.08	0.21	0.10	0.21	0.08	0.21
95%CI (º)	0.06-0.10	0.14-0.27	0.07-0.12	0.15-0.27	0.06-0.10	0.16-0.25

OE; Optoelectronic, Accel; Accelerometer, CI; confidence interval.

Table 3: Range of difference across different frequency cut offs (i.e. 1Hz to 14Hz), mean of difference and 95% confidence interval of the difference between peak ROM values calculated after differing filtering frequency cut offs.

	Differences between Systems					
	All Participants			**Outliers removed**		
Segment	**Upper**	**Lower**	**Lumbar**	**Upper**	**Lower**	**Lumbar**
Mean difference across frequencies (º)	3.99	1.01	3.49	0.74	0.51	0.68
95%CI (º)	3.98-4.00	0.99-1.02	3.49-3.50	0.77-0.79	0.52-0.55	0.68-0.69

OE; Optoelectronic, Accel; Accelerometer, CI; confidence interval.

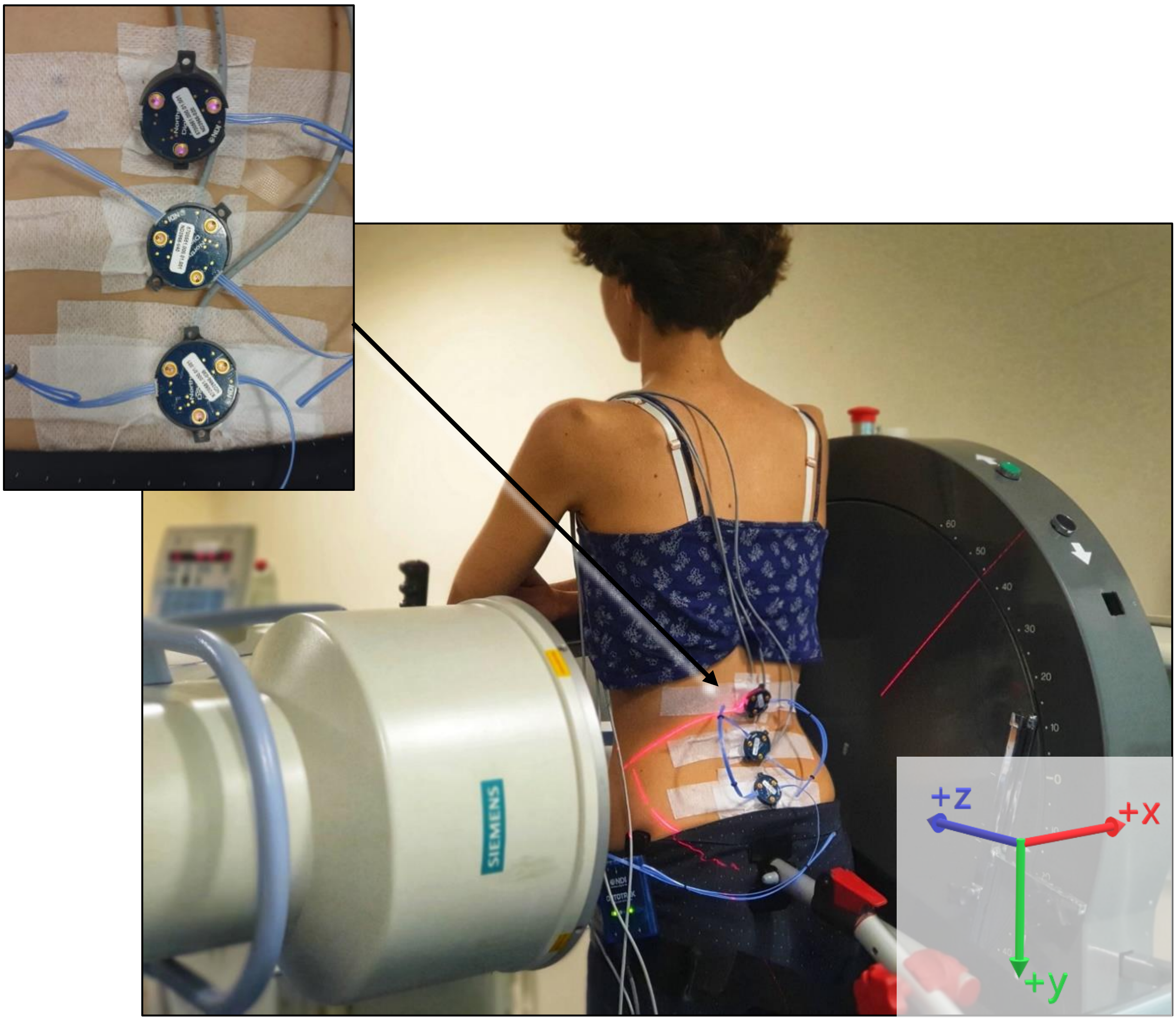

Figure 1. Depicting the motion control platform and the sacral restraint. Inlay depicts the placement of accelerometers overlayed by an optoelectronic system attached to the skin overlying the spinous processes of L2, L4, and S1 vertebrae.

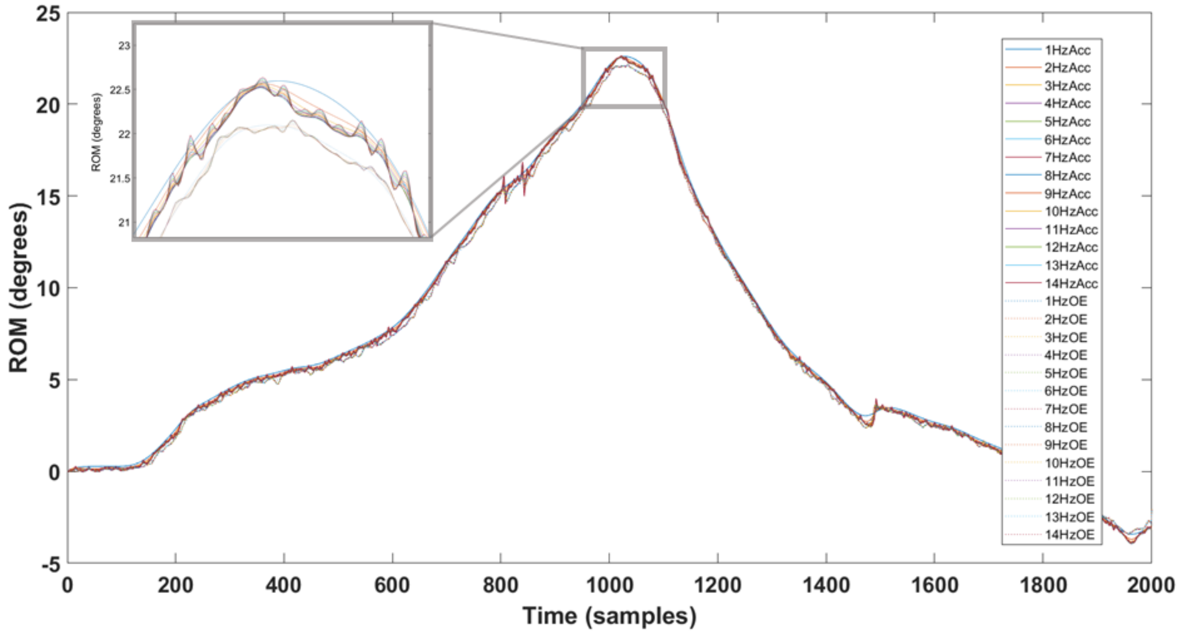

Figure 2. Typical example of motion data for upper lumbar spine (L2-L4) as measured by accelerometers (Acc) and optoelectronic (OE) systems for sequential cut off frequencies using Butterworth filter. Y-axis is change of angular position. X-axis is time. The whole movement was normalised to 2000 using linear interpolation.

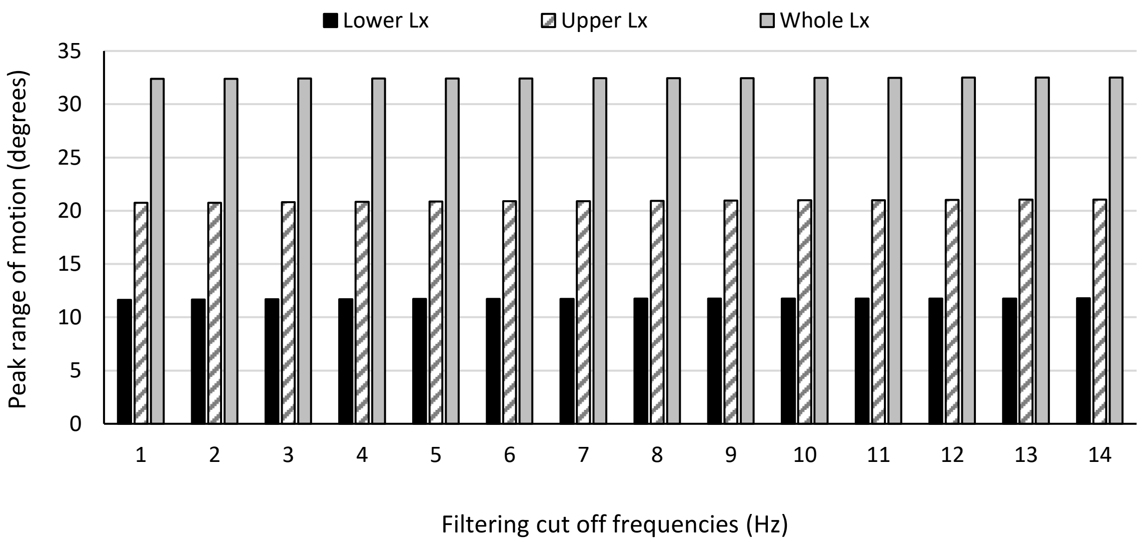

Figure 3. Typical example of peak range of motion data for sequential cut off frequencies for Butterworth filter. Accelerometer example for one participant.

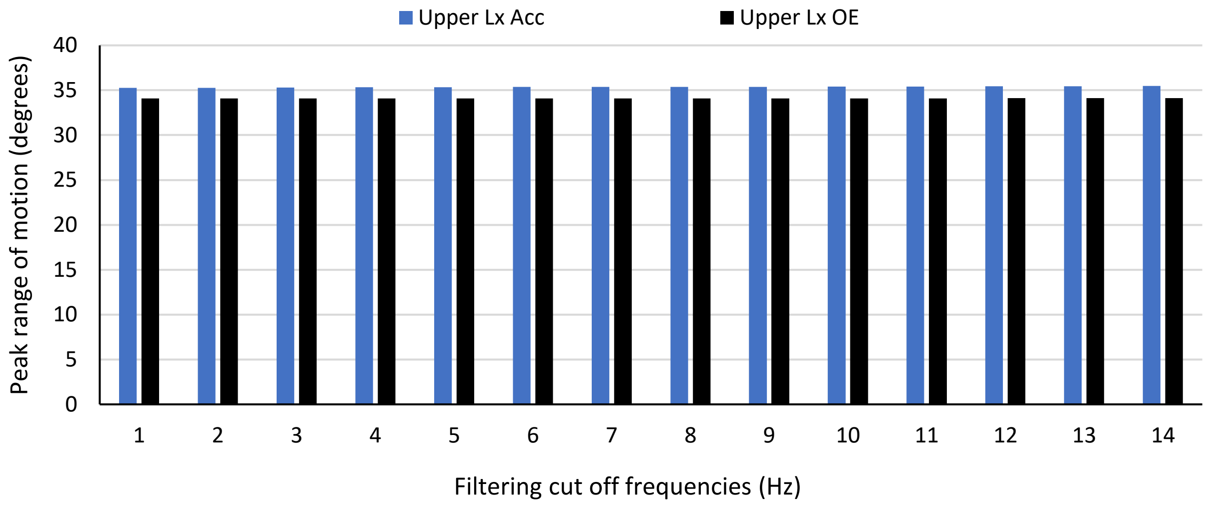

Figure 4. Typical example of one participant of peak range of motion data for upper lumbar spine for sequential cut off frequencies using Butterworth filter. Accelerometer compared to Optoelectronic system.