JOURNAL OF MECHANICAL ENGINEERING AND SCIENCES (JMES)
ISSN: 2289-4659 e-ISSN: 2231-8380
VOL. 14, ISSUE 4, 7600 – 7608
DOI: https://doi.org/10.15282/jmes.14.4.2020.24.0598

ORIGINAL ARTICLE

Comparison of the spine kinematics by defining lumbar as single and multi-segmental in completing critical daily task

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ABSTRACT – The change of the spinal curvature in completing a variety of daily tasks is essential to independent living. There is still a lack of studies highlighting the lumbar segmental contribution during sit-to-stand (STS) and stand-to-flexion (STF) using non-invasive study. The purpose of this study is to compare the spine kinematics by defining lumbar as a single and multi-segmental during continuous daily motion in healthy Asian adults using a non-invasive approach. During STS, most subjects implemented kyphotic lumbar curve during the early stage of motion which revealed poor posture implementation and significant differences in the lumbar kinematics which were only noticeable at specific phases between both approaches. A significant difference in multi-segmental behaviour was observed only at the end of the motion. All three segments displayed different time responses during the transition from kyphotic to lordotic curve. Passive/delayed behavior within the lower lumbar segment was observed between 0-50% of motion completion. During STF, statistically significant differences were found between assuming lumbar as a single and multi-segment in all phases. This in vitro study identified characteristic motion patterns in the lumbar spine during daily motions. The results provided a clear description of the healthy spinal condition of adults and may serve to identify specific multi-segmental contribution.

ARTICLE HISTORY
Received: 12th Feb 2019
Revised: 19th Aug 2020
Accepted: 09th Sept 2020

KEYWORDS
Sit-to-stand;
stand-to-flexion;
multi-segmental;
lumbar;
daily task

INTRODUCTION

The lumbar spine is among the most commonly discussed spinal region, as it plays a vital role in completing daily human activities at home or workplace such as bending, twisting, and supporting a load. Due to excellent mechanical properties and unique vertebra dimensions, the lumbar spine is the most superior spinal region compared to the cervical and thoracic, in terms of rigidity and functionality. The change in spinal curvature when completing a variety of daily tasks is essential to independent living, especially within the lumbar region. Performance of the sit-to-stand (STS) and stand-to-flexion (STF) maneuvers involves the activation of multiple muscles of the lower limb and most notably, the stability contributed by the lumbar spinal region. The ability to translate the body mass from a relatively stable sitting position to the feet, a small base of support during standing is crucial during STS maneuver. STS comprises of two phases, which are pre-extension and an extension phase [1, 2]. An initial generation of horizontal linear momentum is required at the pre-extension phase which will be used to move the upper body mass forward to the feet. As the mass is placed near to the feet, vertical momentum will propel the body mass vertically into standing, triggering the extension phase.

Flexion is the most common movement used as compared to extension, lateral bending, and rotation, where approximately 4400 flexions are performed daily [3]. During forward flexion, anterior and posterior structures are affected by contrary forces. The posterior structure (posterior portion of the disc, posterior ligaments, and muscles) is subjected to compression while the anterior structure is subjected to tension. Posterior outer annulus fibrosus, zygapophyseal joint capsule, and posterior ligaments play a vital function by providing resistance and limiting the bending process [4]. The lumbar spine provides a significantly greater contribution in carrying out flexion motion as compared to the thoracic and cervical regions.

The behavior of the lumbar spine while carrying out daily tasks has been previously investigated in vitro [5-9] and in vivo [10-12]. Most of the works were focused on assuming the lumbar spine as a single segment. This led to the suggestion that the approach is not the best way in presenting the contribution of the lumbar spine towards daily activities. Many hypotheses regarding the contribution of the lumbar spine during STS and STF appear to be ill-defined and debatable, as most of them assume lumbar as only one segment. This resulted in a lack of proper and impractical assessment of the actual lumbar behavior, which is made up of multi-segmental vertebra.

This paper calls into question on the spinal kinematics using two different approaches, assuming lumbar as (1) a single segment and (2) as multi-segmental in completing critical daily tasks among healthy Asian adults. This study makes use of a marker-based motion capture system to explore the behavior of the spine during STS and STF. A study by Papi et al.

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found the spinal segments did not share the same and predictable behavior in a specific daily task [13]. Thus, this study focused on breaking down the region of the lumbar spine into smaller segments to focus on its multi-segmental contribution in completing daily tasks. We hypothesized that the lumbar multi-segmental performance is different compared to the performance when defining lumbar as only a single segment during both types of tasks carried out by healthy Asian adults. Asymptomatic subjects were taken into consideration as a study conducted by Viggiani et al. found the intervertebral angle distributions were less pronounced in upright standing and non-existent in full flexion between healthy and back pain suffering subjects [14].

Related Work

In exploring spinal segment kinematics, the most common method used is radiograph which allows the implementation of the traditional Cobb method, modified Cobb method, computer-assisted method for the deriving radius of lumbar spine curvature, and lumbar vertebral centroid angles [15-17]. These methods provide highly reliable output for medical purposes [18]. The use of radiographic equipment always faced the same problem, which is the wariness of exposure on the subjects and problematic ethics issues, even though this is the golden standard for spinal's angle study. Thus, many research switch to safer approaches, such as Wearable Smart T-shirt [19], garment prototype using strain sensors [20], MRI [21], photogrammetric [22], inclinometers [23, 24], and electromagnetic tracking [26]. A study by Perrott et al. revealed that there are no significant differences between both approaches as they produce almost similar results [27]. Non-invasive approaches have been effective and proven in predicting multi-segmental cervical and lumbar vertebral angles [8, 28-30] and are likely to be implemented nowadays as they are capable to produce highly reliable results [15, 25, 31-33] with only a small percentage of error [24].

METHODS AND MATERIALS

Participants

Nine male healthy subjects [mean age (SD): 24.9 years (5.14)] were recruited from the Shibaura Institute of Technology. Inclusion criteria for healthy subjects were: no musculoskeletal pathologies, body mass index (BMI; calculated as weight[kg] / height^2[m^2]) < 25 kg/m^2, no low back pain symptoms for the preceding 6 months. Mean BMI (SD) of all subjects was: 20.66 kg/m2 (1.68). This project had ethical approval from the Faculty of Biomedical Engineering committee of the author's university, Universiti Teknologi Malaysia (UTM), and informed consent was obtained from participants.

Instrumentation

A 3-D motion capture analysis system with ten high-precision infrared cameras (HWK-200RT camera, Motion Analysis, USA) was used to find the kinematics variables of the lumbar spine. The system provided three-dimensional coordinates of reflective passive markers during the study. The sampling rate was set at 200 [Hz]. A total number of 9 reflective passive markers (diameter: 10 mm) were attached on the spinal column (5 markers: Lumbar 1 to 5) using tape and four reference markers were placed on the testing floor by a single experienced physiotherapist. For STS tasks, an office chair, armless and backless, was adjusted vertically for each subject to obtain the same knee flexion angle (fixed at 90°).

Data management was performed by using specified software (Cortex version 6) then converted into a Microsoft Excel file. Statistical significance and data were analyzed by using Matlab 2016b (Chicago IL, USA). Using the results obtained from MATLAB, the placement of markers on the subjects' body was compared with the literature [34-37] using the image processing method at a standing posture to make sure the vertebra locations were correctly assumed.

Procedure

Task specified for the study is STS and STF. Each subject was asked to complete the task at self-selected speed with the feet self-positioned over the force platform (no fixed distance between the feet was imposed) for 3 acquisition trials. Interval time between each trial was fixed at 5s. The experimental set up is similar to the one proposed by Sibella et al. [38]. The details of the motion sequence are as follow:

(1) STS

Begin from sit (0% of motion completion) to stand (100% of motion completion).

(2) STF

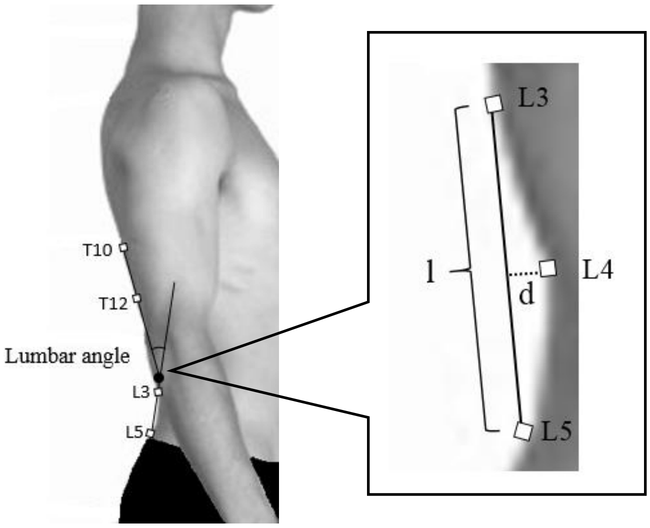
Begin with upright standing (0% of motion completion) to the ventral flexed position (100% of motion completion).

Angle Calculations

The lumbar curvature angle was the index of lumbar lordosis. For this study, two different approaches were used to calculate global and multi-segmental lumbar lordosis during STS and STF. For global lumbar lordosis, the boundary is between T10 to L5, as shown in Figure 1(a). T10 was chosen as the top boundary based on variation in facet joint orientation [39] and radiographs of standing posture [40]. Our global lumbar lordosis calculation bears a close resemblance to the one proposed by Claus et al. [41]. For a multi-segmental study, the angle studied is defined as angular displacement. The method used to obtain the multi-segmental angular displacement of the lumbar is essentially the same as that used by Sorensen et al. with some proper alterations for other lumbar segments [42]. The multi-segmental angular displacement was obtained by (1) calculating the distance of vector (l) from L3 to L5, (2) obtaining a second vector of distance (d) that is perpendicular from l to L4, (3) using the formula: $2\arctan(0.5l/d)$ [43] and (4) subtracting the obtained value with 180° so that a larger angle would equal larger lumbar lordosis (Figure 1(b)).

Statistical Analyses

The mean and standard deviation of all angular displacement was calculated. Statistical differences of angular displacement in different phases between global lumbar lordosis and lumbar segmental were calculated using a one-way analysis of variance. For all statistical comparisons, p-values <0.05 were considered significant.



(a) (b)

Figure 1. (a) Global lumbar lordosis boundary (b) Segmental lumbar vectors

RESULTS

Lumbar's Measurement Technique

Each lumbar segment has different behavior and not all of them contribute to the same lordosis curve while some of them behave with kyphotic manner even at the same percentage of completion. Literatures [41, 44-46] use different approaches in measuring the global lumbar lordosis which is either (1) by measuring the angle as a result of differentiating two straight-line angles between two known boundaries and (2) using three-point measurements as the segmental measurement in this study. The only deficiency of the latter formula is that it is only applicable to a small range of points in between. Additionally, applying this method to measure global lumbar lordosis between T10 to L5 will not provide the actual lumbar lordosis angle. For this study, the lumbar curve is divided into three segments (Upper segment: T10-L1, Middle segment: L1-3, Lower segment: L3-5) and the mean values (with standard deviation) were shown in Table 1 and Table 2.

Lumbar as a Single Segment (T10-L5)

(a) STS

The transition of the global lumbar curve during STS is significantly different when studied as different segments compared to a single segment. Most subjects implemented the kyphotic lumbar curve at the initial phase (8.38 ± 7.93°) which was due to the absence of lower back support. The curve then gradually decreases to a lordotic curve until reaching 100% of motion completion (-11.71±4.80°) as elucidated in Figure 2(a). Lord et al. noted that lumbar lordosis during sitting was nearly 50% lower on average as compared to standing lumbar lordosis [47]. Our results do not appear to corroborate with the finding of Lord et al. In fact, the results showed approximately 70% on average than standing. The use of asymptomatic subjects in the present study could well be responsible for this result, as Lord et al. focused on reporting subjects suffering from back pain. An "ideal" form of lumbar transition from kyphotic to lordotic curve, which can be observed, occurred at 50% of motion completion. The lumbar spine begins to extend during buttock's liftoff, which resulted in a higher lumbar spine curve's value at the end (100%) compared to the initial phase (0%). Significant differences in the lumbar kinematics during STS were only noticeable at 0%, 75%, and 100% (P-value < 0.05) of motion completion between both approaches used in this study.

(b) STF

The transition from lordotic to the kyphotic curve was completed before achieving 25% of motion completion as shown in Figure 2(b). Linear increment towards the kyphotic curve was observed at the beginning of motion until reaching 50% of motion completion. The increment in motion speed tends to slow down upon 50% of motion completion. Upon reaching 75% of motion completion, no change in angle was observed and it was maintained until reaching 100% of motion completion. The initial (0%) to intermediate (50%) motion transition showed a significant change in the global lordosis angle. Unfortunately, it was impossible to highlight the actual vertebra contributing to the change if the lumbar was only studied as a single segment. Also, the results discovered delayed or passive behavior of global lordosis acting between 50% to 100% of motion transition. Statistically significant differences were found (P-value<0.05) between assuming lumbar as a segment and multi-segment in all phases.

Lumbar Multi-Segments

(a) STS

Statistical study revealed that there are no significant differences within segments between 0% to 75% of motion completion (P-value: 0.43 (0%), 0.60 (25%), 0.64 (50%), 0.61 (75%)). However, there is a significant difference (P-value < 0.05) for the multi-segmental behaviour at 100% of motion completion.

Carr highlighted the segmental contribution of the spine during standing up. However, the biomechanical analysis indicated that movement at the spinal joints is minimal [48]. The present study focused on highlighting the segmental contribution of the lumbar spine during STS since there is a lack of literature exploring it. From Figure 3(a), the upper segment (T10-L1) played a vital inclination point from kyphotic to lordotic curve for the lumbar region as it is located within the thoracolumbar joint. This segment only showed a peak increment towards the lordosis curve at 50% of motion completion and maintained passive behavior with minimal changes (Δ less than 2°) in angle within the early and end of motion completion. Interestingly, this segment showed the slowest motion transition (kyphotic to lordotic) compared with the other two segments and concluded to be inactive before and after 50% of the motion completion phase due to its poor contribution during the transition. Presumably, the passive behavior of this segment was due to the extension of the thoracic spine along with the flexion of the lumbar spine during STS [46]. The transition to lordotic behavior for this segment only occurred after 75% of motion completion, thus validating point T10 as the top inclination point of the lordosis curve.

During early transition (0-25%), the middle lumbar segment (L1-3) tend to show early contribution during the transition with the highest angular displacement increment (Δ more than 2°). Compared to the other two segments, this segment showed the quickest response to change from kyphotic to lordotic curve, which occurred before reaching 25% of motion completion. This segment contributed more than 50% of the lumbar lordosis angle at the end of the motion. The result concluded that this part is active and has the highest mobility during STS. Latter response can be observed within the lowest segment (L3-5) compared to the middle segment, up until reaching 50% of motion completion with minimal changes (Δ less than 2°). The results showed that the passive/delayed behavior of the L3-5 segment within this period (0-50%) and a peak of motion can be observed after 50% of motion completion. The delay of angular displacement increment within this segment appears to indicate the translation from horizontal to vertical momentum [48]. The translation is necessary to move the upper body mass which includes trunk, torso, and head mass forward to the feet. The translation is essential as it provides initial stabilization which results in a delay of response within the lower lumbar segment. The peak increment of angle only occurred at 75% of motion completion and was maintained until the end of the motion. All three segments displayed different time responses based on anatomical and functional reasons during the transition from kyphotic to lordotic curve with the middle segment showing the quickest transition.

(b) STF

The statistical study revealed that there were significant differences at 75% and 100% of motion completion between segments (P-value<0.05). The upper lumbar segment (T10-L1) showed passive behavior with minimal changes (Δ less than 2°) in angular displacement compared to the middle and lower lumbar segments (Figure 3(b)). This segment was concluded to be inactive and has the lowest contribution during flexion maneuver. The delayed and passive behavior of this segment was due to the anatomical location as this segment which serves as the connection that linked the thoracic kyphosis and lumbar lordosis or known as thoracolumbar. The thoracic curve is not affected as much as the lumbar curve during the forward bend, thus results in the passive behavior of the peak lumbar segment. Middle (L1-3) and lower (L3-5) lumbar segments displayed approximately similar behavior but a quicker change in angular displacement was observed within the lower lumbar segment. Interestingly, the peak of change in angular displacement of the middle segment was observed specifically at 25% to 75% of motion completion. This segment had a moderate contribution to the motion transition, hence concluded to be an active segment.

Lower segment (L3-5) displayed higher mobility compared to the middle segment which displayed a slower time response. Lower lumbar segment and global lumbar lordosis displayed approximately similar patterns at the early phase of motion (0-25%) with no statistically significant difference found (P-value<0.05). A gradual increment of angular displacement was observed throughout task completion within this segment. The peak angular displacement increment was also observed at 50% of motion completion, thus highlighting the vital contribution of the lower segment to the overall change in lumbar lordosis and concluded to be an active segment. High mobility behavior displayed by the lower lumbar region is barely distinguishable from [49] who found strong correlations between the lower lumbar (L3-S1) spine range of motion (ROM) during flexion.

Table 1. Change in lumbar's angular displacement during sit-to-stand (STS)

	Motion Percentage				
Lumbar Segment	0%	25%	50%	75%	100%
T10-L5	8.38±7.93	6.02±7.29	-0.33±7.84	-7.11±6.90	-11.71±4.80
T10-L1	4.90±6.04	3.72±5.80	1.34±4.84	1.50±5.91	-0.05±5.17
L1-3	0.38±5.12	-1.75±7.03	-2.09±5.87	-4.23±5.82	-4.76±5.08
L3-5	2.94±3.92	2.13±4.41	1.05±3.98	-1.49±4.08	-1.71±3.44

* Values are presented as mean ± standard deviation

Table 2. Change in lumbar's angular displacement during stand-to-flexion (STF)

	Motion Percentage				
Lumbar Segment	0%	25%	50%	75%	100%
T10-L5	-6.46±7.82	6.97±8.94	21.16±8.87	25.69±7.68	26.16±7.92
T10-L1	2.07±3.43	3.72±2.32	4.39±2.78	2.86±5.13	3.24±4.24
L1-3	-0.44±2.86	0.87±3.86	3.97±3.58	5.35±2.31	4.82±3.23
L3-5	-1.11±4.68	2.17±3.62	6.26±2.15	7.92±2.04	4.82±2.73

* Values are presented as mean ± standard deviation
*Negative and positive value indicates lordotic and kyphotic curve respectively.

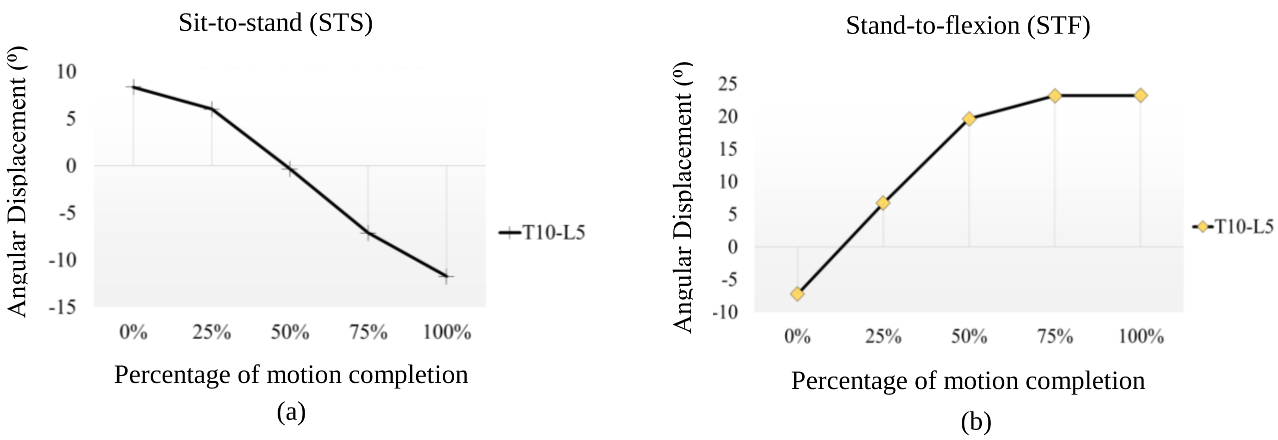
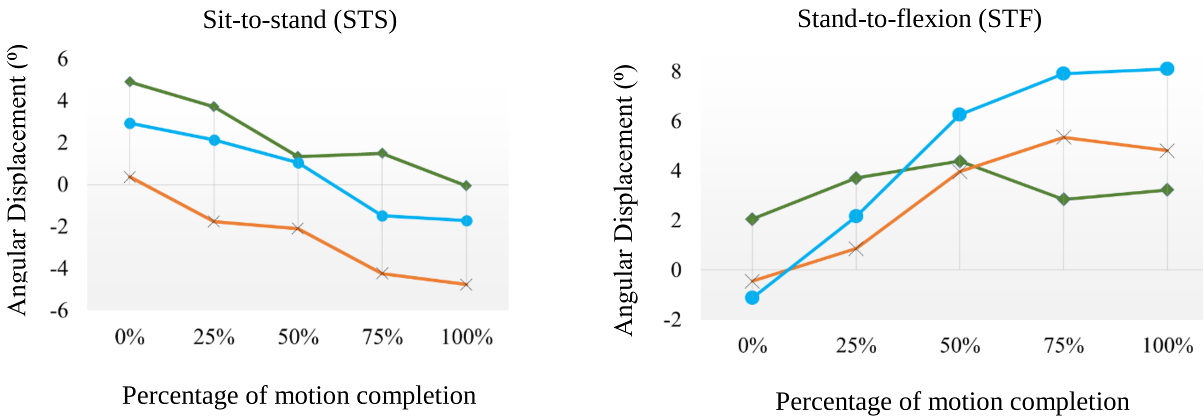
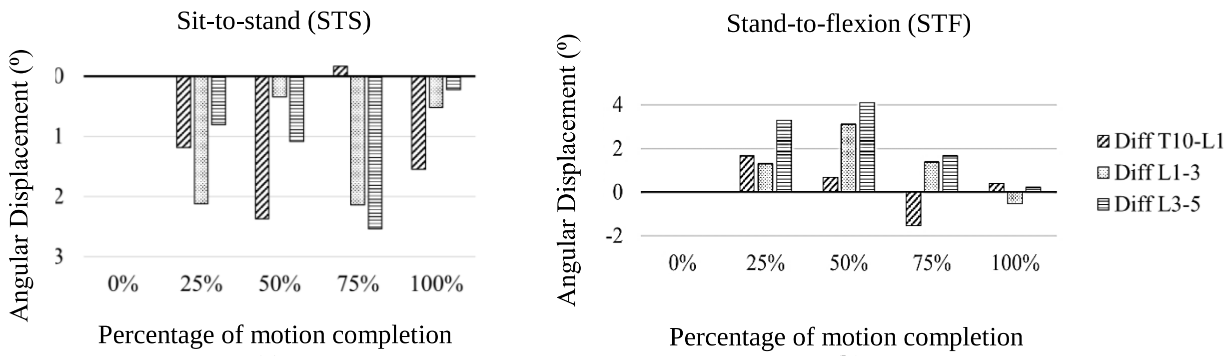


Figure 2. Global lumbar transition during: (a) sit-to-stand (STS) and (b) stand-to-flexion (STF)



(a) (b)

Figure 3. Segmental lumbar transition during: (a) sit-to-stand (STS) and (b) stand-to-flexion (STF)
*Positive and negative value indicate kyphotic and lordotic lumbar curve respectively.



(a) (b)

Figure 4. Segmental angular displacement increment/decrement during: (a) sit-to-stand (STS) and (b) stand-to-flexion (STF)

CONCLUSIONS

A single segment to distinguish the actual segmental behavior of the lumbar spine without highlighting the differences in segmental contribution in motion was studied upon. This study found that the lumbar curve tends to implement an "ideal" spinal transition from kyphotic to lordotic at 50% of motion completion during STS. The multi-segmental approach revealed that the upper lumbar segment tends to exhibit passive behavior with the slowest transition from kyphotic to lordotic curve. The middle lumbar segment showed a significantly higher contribution towards motion completion with the quickest behavioral response and was found to have the highest mobility compared to the other two segments. The results also found passive/delayed behavior of the last lumbar segment (L3-5) which starts at the beginning (0%) up to 50% of motion completion. Statistical results revealed that there were no significant differences at 25% and 50% of motion completion for both approaches (assumed as a segment and multi-segmental). Significant differences in the lumbar kinematics during STS were only noticeable at 0%, 75%, and 100% of motion completion for both approaches. The actual behavior of lumbar curves can only be studied critically by approaching them as different segments as each segment showed significantly different behavior during STS. Also, this multi-segmental approach was able to successfully distinguish between the segmental contribution during motion transition. This finding successfully highlighted the importance of identifying segmental rather than acknowledge the global lordosis contribution in completing specific tasks.

Limitations and Future Works

As three motion readings were taken, it is very important to train the subject properly so that he/she can give the same posture during the experiment which would lead to a more accurate average reading. For future works, the number of subjects and diversity of subjects in terms of age group should be considered for study on the spinal-age relation, especially for Asian populations. Given that this finding is based on a limited number of subjects, the results from such analyses should be treated with consideration as this profile only represents a minor fraction of the daily sagittal alignment in Asian sedentary society. These findings might be important to develop dynamic orthotic devices and to increase the awareness of the biomechanical challenges that spinal structures and implants face in real-life. Furthermore, long-term assessments of spinal alignment and motion during daily life can provide valid data on spinal function and can reveal the importance of influential factors.

ACKNOWLEDGMENTS

This research study was supported by Fundamental Research Grant Scheme (FRGS) R.J130000.7824.4F839 and Tier 1 Grant Q.J130000.2524.20H25, Universiti Teknologi Malaysia (UTM). The authors would like to thank Shibaura Institute of Technology (SIT), Japan for access to their laboratory facilities and assistance during the completion of this research study and gratitude towards the Universiti Teknologi Malaysia (UTM).

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