Three-dimensional spine kinematics during multidirectional, target-directed trunk movement in sitting

ARTICLE *in* JOURNAL OF ELECTROMYOGRAPHY AND KINESIOLOGY: OFFICIAL JOURNAL OF THE INTERNATIONAL SOCIETY OF ELECTROPHYSIOLOGICAL KINESIOLOGY · SEPTEMBER 2009

Impact Factor: 1.65 · DOI: 10.1016/j.jelekin.2009.07.005 · Source: PubMed

2 AUTHORS:


Richard Arthur Preuss
McGill University


Milos R Popovic
University of Toronto

Journal of Electromyography and Kinesiology xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Three-dimensional spine kinematics during multidirectional, target-directed trunk movement in sitting

Richard A. Preuss *, Milos R. Popovic

Rehabilitation Engineering Laboratory, Lyndhurst Centre, Toronto Rehabilitation Institute, 520 Sutherland Drive, Toronto, Ontario, Canada M4G 3V9
Rehabilitation Engineering Laboratory, Institute of Biomaterials and Biomedical Engineering, University of Toronto, 164 College Street, Toronto, Ontario, Canada M5S 3G9

A R T I C L E   I N F O

Article history:
Received 25 November 2008
Received in revised form 14 July 2009
Accepted 17 July 2009
Available online xxxx

Keywords:
Biomechanics
Movement
Spine
Assessment technology

A B S T R A C T

The current study provides a quantitative assessment of three-dimensional spine motion during target-directed trunk movements in sitting. Subjects sat on an elevated surface, without foot support, and targets were placed in five directions, at three subject-specific distances (based on trunk height). Subjects were asked to lean toward the target, touch it with their head, and return to upright sitting. A retro-reflective motion analysis system was used to measure spine motion, using three kinematic trunk models (1, 3 and 7 segments). Significant differences were noted in the total trunk motion measured between the models, as well as between target distances and directions. In the most segmented model, inter-segmental trunk motion was also found to differ between trunk levels, with complex interaction effects involving target distance and direction. These findings suggest that inter-segmental spine motion is complex, task dependent, and often unevenly distributed between spine levels, with motion patterns differing between subjects, even in the absence of pathology. Use of a multi-segmental model provides the most interpretable findings, allowing for differentiation of individual motion patterns of the spine. Such an approach may be beneficial to the understanding of movement-related spine pathologies.

1. Introduction

Recent innovations in motion capture technology – such as inertial sensors (Lee et al., 2003; Goodvin et al., 2006), electromagnetic sensors (Pearcy and Hindle, 1989) and optoelectronic systems (Andreoni et al., 2005) – provide a means to objectively quantify spine motion, in three-dimensions, during movement. These have the potential to expand our understanding of spine-related impairments, and increase the feasibility of quantitative, patient-specific assessment of spine kinematics for a wide range of pathologies.

Technologies using multiple sensors (or markers) allow for the simultaneous measurement of motion, in three-dimensions, across multiple spine levels, and for a multitude of complex tasks. Despite this, research using these technologies has typically focused on relatively large spine regions (Pearcy and Hindle, 1989; Pearcy, 1993; Russell et al., 1993; Swinkels and Dolan, 1998; Van Herp et al., 2000; Lee, 2001; Lee et al., 2003; Preuss and Fung, 2008; Hsu et al., 2008), treating these as single, flexible segments. Furthermore, the movements studied often isolated to the cardinal planes (Pearcy and Hindle, 1989; Russell et al., 1993; Willems et al., 1996; Van Herp et al., 2000; McGregor et al., 2001; Troke et al., 2001; Lee et al., 2003; Hsu et al., 2008), with limited attention paid to off-axis, coupled motions (Pearcy and Hindle, 1989; Russell et al., 1993; Willems et al., 1996; Lee et al., 2003).

The purpose of the current study was to assess the motion of the spine in young, healthy subjects, in three-dimensions, during multi-directional target-directed movements of the trunk. The task was designed to approximate the movements required in the trunk when reaching beyond arm's length in various directions and distances. Specific goals were to assess the effect of segmentation on the total measured spine motion (i.e., how the number of divisions in the spine model affects the overall measurement), and to assess the relative motion of the spine at different levels. A secondary goal was to determine the variability of spine motion in a healthy subject population, and consequently the usefulness of such an approach as a tool to assess spine motion in individual patients.

2. Methods

2.1. Subjects

Eleven healthy volunteers (Table 1) were recruited from a convenient sample of research staff and students at a rehabilitation hospital. Exclusion criteria were: (a) back pain at the time of

* Corresponding author. Address: Rehabilitation Engineering Laboratory, Lyndhurst Centre, Toronto Rehabilitation Institute, 520 Sutherland Drive, Toronto, Ontario, Canada M4G 3V9. Tel.: +1 416 597 3422x6902, +1 514 489 7336; fax: +1 416 425 9923.
E-mail address: richard.preuss@toronto-fes.ca (R.A. Preuss).

1050-6411/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jelekin.2009.07.005

Table 1
Subject characteristics.

Gender	Age	Trunk height (m)	Depth of base (m)	Width of base (m)
F	30	0.76	0.43	0.42
F	30	0.76	0.45	0.43
F	29	0.71	0.45	0.43
F	28	0.72	0.45	0.46
M	24	0.72	0.45	0.39
M	24	0.75	0.48	0.44
M	26	0.79	0.49	0.43
M	34	0.71	0.48	0.38
M	26	0.76	0.46	0.42
M	32	0.82	0.48	0.43
M	31	0.80	0.52	0.49
Mean	28.5	0.75	0.47	0.43
St. dev.	3.3	0.04	0.03	0.03

Base = area under the thighs and buttocks.
Trunk height = support surface to base of occiput.

testing; (b) history of back pain persisting for more than 3 months and interfering with daily activity; (c) previous diagnosis of any musculoskeletal condition affecting the spine (e.g., spodylolysthesis, scoliosis) or hips; and (d) history of any neurological, vestibular or other condition affecting balance. All subjects provided written, informed consent prior to participation. Ethics approval was received from the local ethics committee.

2.2. Experimental task

Subjects sat on a rigid, elevated surface, with the thighs supported to 75% of the distance from the greater trochanter to the lateral epicondyle of the femur. The lower legs hung freely, with no foot support. No other support or constraints to movement were provided.

Twenty-two reflective markers (10 mm diameter) were placed along the length of the subject's spine to monitor trunk motion (Fig. 1C – model described in Subsection 2.3 below). Five larger markers (25 mm diameter) were suspended from the ceiling, at 45° intervals anterior to the frontal plane (Fig. 1A), to act as targets for the movement task. Three subject-specific target distances and heights were based on the distance from the support surface to the base of the subject's occiput, in sitting. These represented 15° intervals of angular motion (Fig. 1B), based on movement as an inverted pendulum. Targets were first placed at the closest target distance, and moved to the next distance once all trials had been completed. For each target distance, three trials in each direction were performed, in a randomized order. Key anthropometric data for each subject (trunk height and dimensions of the base of support under the thighs and buttocks) are presented in Table 1.

For each trial, the subject was instructed to first look at the specified target, then lean toward it in order to touch it with his/her head, and return to the initial upright sitting position. No specific instructions were given regarding how to look at the target (i.e. head and/or trunk rotation was not specified). The subjects were, however, instructed to not look at the target throughout the arc of movement, so as not to artificially constrain cervical and thoracic motion. The subjects moved at a self-selected, comfortable pace, and were instructed to keep their lower legs hanging vertically downward, so as not to be used as a counterweight for trunk movement.

2.3. Data acquisition and kinematic model

Marker position was acquired using a 6-camera Vicon (Oxford, UK) 512 motion analysis system (sampling frequency 120 Hz), and subsequently low-pass filtered using an 8th order, dual-pass Butterworth filter, with a low-pass cut-off frequency of 2 Hz.

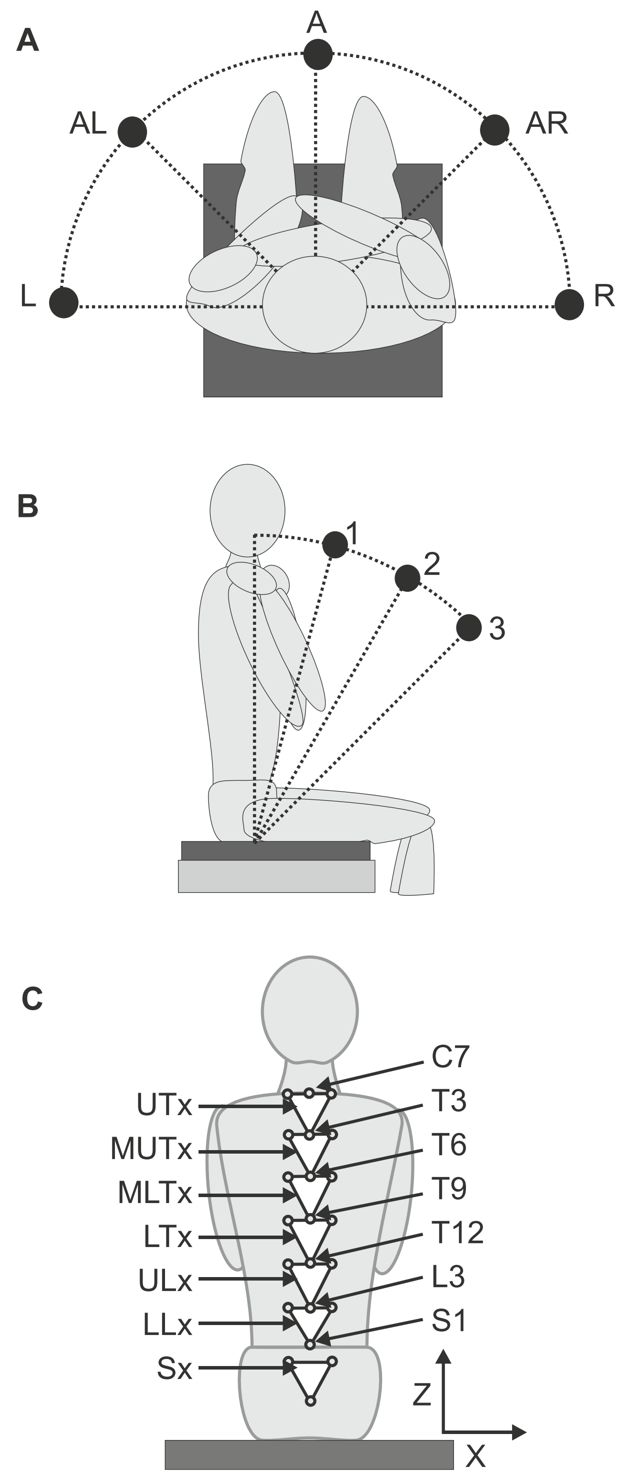

Fig. 1. (A) Target directions for the movement task. Targets were placed bilaterally in the frontal plane (left – L and right – R), at 45° anterior to the frontal plane (anterior-left – A-L and anterior-right – A-R), and anterior to the subject in the sagittal plane (A). (B) Target distances and heights for the movement task. Trunk motion was approximated as an inverted pendulum, and targets were placed at three subject-specific distances, representing 15° intervals of angular motion based on a measurement of trunk height from the support surface to the base of the subject's occiput. (C) Marker placement and spine segmentation for the kinematic models of spine motion.

The markers along the subject's spine were divided into groups of three (marker triads), which were used to define seven trunk segments (Fig. 1C). The sacral (Sx) segment was defined by the markers over the posterior superior iliac spines and the 5th sacral vertebra. The lower lumbar segment (LLx) was defined by markers placed at least 50 mm lateral to the spinous process of the 3rd lumbar vertebra (L3) and over the 1st sacral vertebra. Moving rostrally, each successive segment was defined by a centrally placed marker below, and two laterally placed markers above. These markers were placed over, and lateral to, the spinous processes of the 3rd lumbar vertebra (L3), the 12th, 9th, 6th and 3rd thoracic vertebrae (T12, T9, T6 and T3) and the 7th cervical vertebra. The segments defined by these marker groups were termed upper lumbar (ULx), lower thoracic (LTx), mid-lower thoracic (MLTx), mid-upper thoracic (MUTx) and upper thoracic (UTx).

A Cartesian axis system was created for each trunk segment, with the *X*-axis running left to right, parallel to a line between the two upper markers, the *Z*-axis running caudal to rostral, parallel to a line between the caudal marker and the mid-point between the two rostral markers, and the *Y*-axis running from posterior to anterior, defined by the cross product of the *Z* and *X*-axes. All calculations of segment orientation were for a rostral segment relative to a caudal segment. Segment orientation was first calculated about the *X*-axis (flexion), followed by the *Y*-axis (side-bending) and *Z*-axis (axial rotation), following orthopaedic convention. The motion about the *X* and *Z*-axes were then multiplied by -1 to represent forward flexion and axial rotation to the right as positive (side-bending to the right was also represented as positive). All calculations were performed using Bodybuilder software (Vicon Motion Systems, Oxford, UK). The residual camera calibration for marker position, for all subjects, was below 0.5 mm, and all markers within a group were spaced at least 100 mm apart. The orientation in space of each segment, therefore, was estimated as accurate to <0.6°, and the orientation of one segment relative to another as accurate to <1.2°.

Trunk motion was modelled using three kinematic models. The Whole-Trunk model measured the total trunk motion based on the orientation of the UTx segment relative to the Sx segment. Previous studies employing this model of trunk motion include (Newcomer et al., 2001; Allison and Fukushima, 2003; Goodvin et al., 2006). The Lumbar–Thoracic model measured the motion of the lumbar spine based on the orientation of ULx relative to Sx, and of the thoracic spine based on the orientation of UTx relative to ULx. Total trunk motion was then represented as the sum of the movements (flexion, side-bending and axial rotation) at the lumbar and thoracic levels. Previous studies employing this model of trunk motion include (Hsu et al., 2008). Finally, the multi-segmental model measured the orientation of each trunk segment relative to that of the segment below, with the movements named for the more rostral trunk segment (e.g. movement of ULx represents the orientation of ULx relative to LLx). Total trunk motion was then represented as the sum of the inter-segmental motions at all six trunk segments within the model. No other study that we are aware of has employed such a detailed assessment of total trunk motion, although previous studies have employed multi-segmental models of the spine (Swinkels and Dolan, 1998; Preuss and Fung, 2008), and detailed analyses specific spine regions (Willems et al., 1996; Gatton and Pearcy, 1999).

2.4. Data analysis

All statistical analyses were performed on the values measured at the point of peak trunk motion. This point was determined as the point of maximum excursion of the centrally placed C7 marker, in the plane defined by the *X* and *Y*-axes of the Sx segment (Fig. 1C). An α-level of 0.05 was used for all statistical analyses.

2.4.1. Total trunk motion

Statistical analyses of total trunk flexion, side-bending and axial rotation were each conducted using three-way ANOVA. The independent variables tested were the kinematic model used to determine the total motion of the trunk (three models), the target distance (three distances) and the target direction (five directions). For target directions to the left, the angles for movements about the *Y* and *Z*-axes (side-bend and axial rotation, respectively) were multiplied by -1 so that left side-bend and left rotation were positive. For all other target placements, right side-bend and right rotation were considered positive.

2.4.2. Inter-segmental trunk motion

Analyses of inter-segmental trunk flexion, side-bending and axial rotation were also performed using three-way ANOVA, based on the measurements derived from the multi-segmental model. The independent variables tested were trunk level (six levels: LLx to UTx), target distance (three distances) and target direction (five directions). As above, for target directions to the left, left side-bending and left axial rotation were treated as positive, while right side-bend and rotation were considered positive for all other target directions.

A Bonferroni post-hoc test for differences between means was also performed, in order to assess the symmetry of motion in side-bending and rotation. The analyses of interest were the effect of target direction for target placements to the left and to the right of the sagittal plane (at 45° and at 90°).

3. Results

All subjects successfully completed each movement task, with the exception of the movements toward the targets in the frontal plane (L and R – Fig. 1A) at distance 3 (Fig. 1B), where none of the subjects was able to reach the target. Trunk motions for these two target placements, therefore, represent the maximum voluntary trunk motions for these subjects, under these test conditions.

3.1. Total trunk motion

Total trunk motion in each axis, for each of the models tested, is illustrated in Fig. 2A. Values for the multi-segmental alone are illustrated in Fig. 2B, to better highlight the effects of distance and direction. The *p*-value for all significant effects was <0.001.

Results of the ANOVA for total trunk flexion revealed main effects for each of the independent variables tested, but no significant interaction effects. In general, spine flexion increased with increasing target distance (main effect of distance) and decreased with more lateral target placement (main effect of direction). The main effect of the model used to measure trunk flexion was most evident for movements toward the laterally placed targets, where those models with fewer segments measured a greater degree of total trunk flexion.

Results of the ANOVA for both total trunk side-bending and axial rotation revealed main effects for distance and direction, but no main effect for the model used to measure these motions. Increased target distance lead to an increase in both side-bending and axial rotation (main effects of distance), as did a more lateral target placement (main effects of direction). For side-bending, a significant interaction effect was also found between distance and direction. This reflects the more pronounced difference in the range of side-bending at distances 2 and 3, compared with distance 1, for the 45° (A-R and A-L) and 90° (R and L) target placements. For axial rotation, no such interaction effect was found, indicating that the effect of target direction was similar at all distances. No other significant interaction effects were found for either trunk motion.

Please cite this article in press as: Preuss RA, Popovic MR. Three-dimensional spine kinematics during multidirectional, target-directed trunk movement in sitting. J Electromyogr Kinesiol (2009), doi:10.1016/j.jelekin.2009.07.005

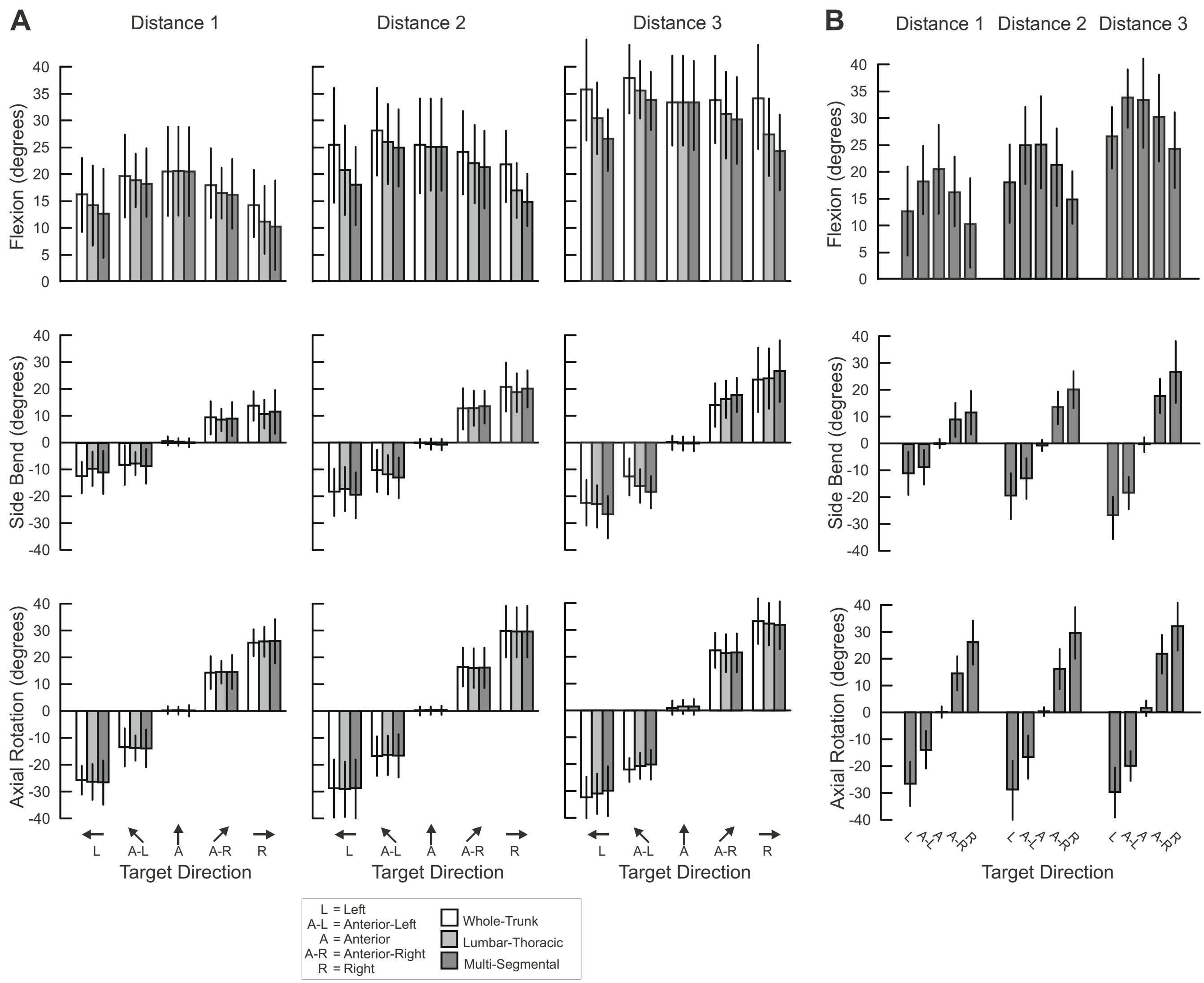

Fig. 2. (A) Total trunk motion measured at the point of peak trunk motion. Bars represent the mean total trunk motion for the subject population, for each of the three kinematic models. Error bars represent a range of plus or minus one standard deviation. The Whole-Trunk model represents the total trunk motion based on the orientation of the UTx segment relative to the Sx segment. The Lumbar–Thoracic model represents the sum of each movement at the lumbar (ULx relative to Sx) and thoracic (UTx relative to ULx) levels. The multi-segmental model represents the sum of the inter-segmental motions at all six trunk segments within the model. (B) Total trunk motion measured at the point of peak trunk motion for the multi-segmental model of the trunk, provided to highlight the significant effects of target distance and direction.

3.2. Inter-segmental trunk motion

Inter-segmental motion, measured by the multi-segmental model, is illustrated in Fig. 3. The p-value for all significant effects was <0.001.

Results of the ANOVA for inter-segmental flexion revealed main effects for each of the independent variables tested, as well as two significant interaction effects. The main effect of trunk level reflects a general tendency toward more flexion occurring at caudal levels, while the main effect of distance reflects a similar tendency toward increasing flexion with increased target distance. The significant interaction effect between these two variables likely reflects the more pronounced effect of increased target distance at the caudal trunk levels. Target direction also had a significant effect on inter-segmental trunk flexion. This effect, however, was complex, as indicated by the significant interaction effect between target direction and trunk level. The most evident contrast was between the LLx and MLTx levels. At LLx, trunk flexion was largest for movements toward anteriorly placed targets, with a progressive decrease in flexion for more lateral target placements. The opposite, however, was seen at MLTx, where a relative increase in inter-segmental flexion occurred for more lateral target placements. In general, flexion was greatest at the most caudal trunk levels for movements toward targets placed in the sagittal plane, while more lateral target placements lead to a relative increase in flexion in the mid-thoracic levels, and a concomitant decrease in flexion at lumbar levels. No interaction effect was found for target distance and direction, and no three-way interaction effect was found, indicating that the effect of target direction was consistent across target distances.

Results of the ANOVA for inter-segmental side-bending revealed main effects for each of the independent variables tested, as well as two-way interaction effects between each of these variables. Side-bending, in general, was greater at the more caudal spine levels (main effect of level), increased with increasing target distance (main effect of distance), and increased with more lateral target placement (main effect of direction). The interaction effect between level and distance reflects the more pronounced increase

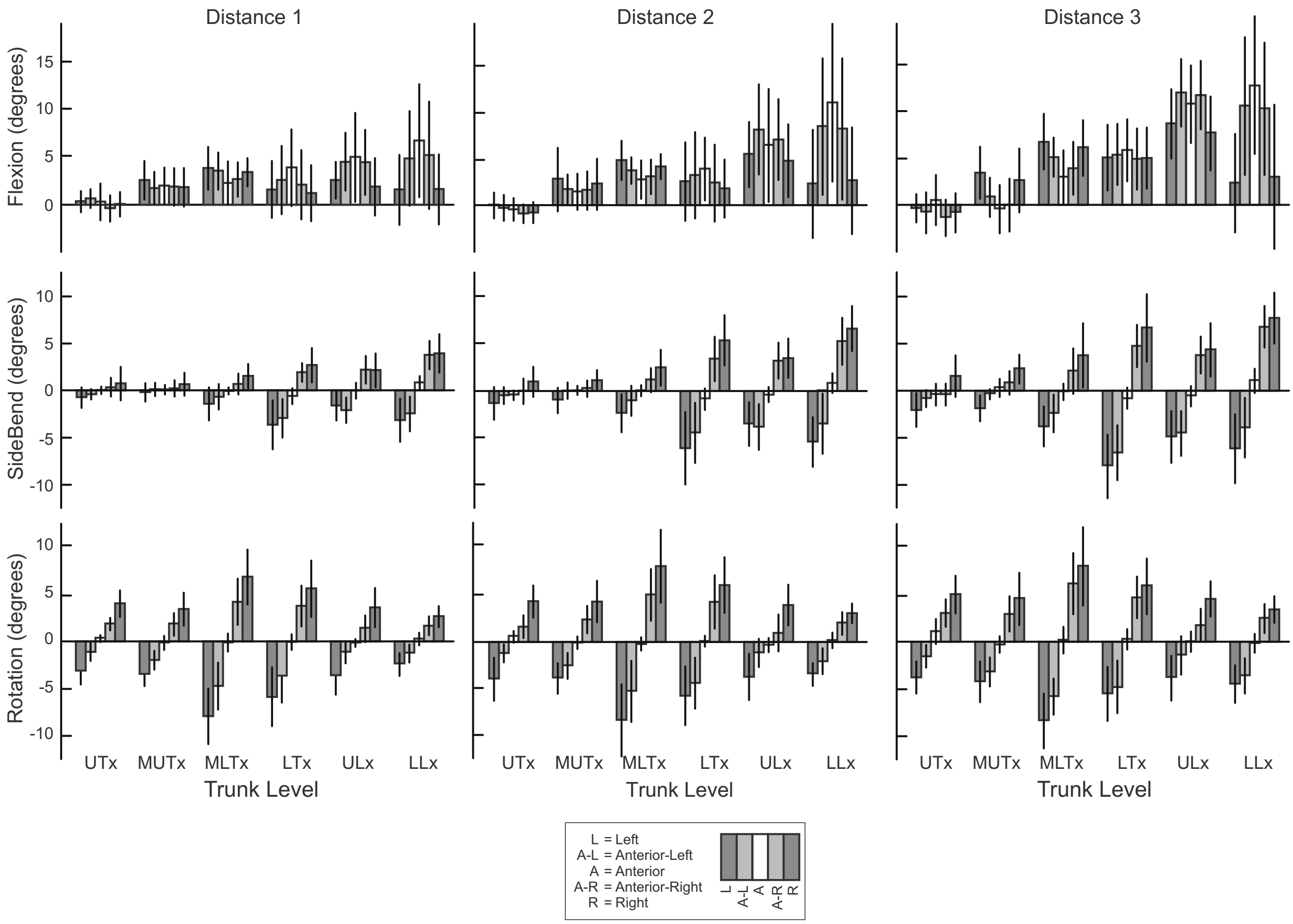

Fig. 3. Inter-segmental trunk motion measured at the point of peak trunk motion, using the multi-segmental kinematic model. Bars represent the mean trunk motion for the subject population, for the five target directions. Error bars represent a range of plus or minus one standard deviation.

in side-bending at the more caudal trunk levels with increased target distance; in particular at LLx and LTx. The interaction effect between level and direction reflects the differing impact of more lateral target placement (45° vs. 90° from the sagittal plane) at the different trunk levels (e.g. LTx vs. ULx). Similarly, the interaction effect between distance and direction reflects the more pronounced difference in side-bending, for the 45° vs. 90° target placements, at distances 2 and 3 compared with distance 1. There was, however, no significant three-way interaction effect between the independent variables tested.

Results of the ANOVA for inter-segmental axial rotation also revealed main effects for each of the independent variables tested, as well as a two-way interaction between trunk level and target direction. Trunk axial rotation was generally greatest at the MLTx level, with a progressive decrease at more caudal and rostral levels (main effect of level). Target direction also had a significant main effect on axial rotation, with increased rotation for more lateral target placements. The interaction effect between these two variables likely reflects the greater inter-subject variability in axial rotation at thoracic levels compared with lumbar levels, for movements toward targets placed at 45° vs. 90° from the sagittal plane. Target distance also had a main effect on the degree of trunk axial rotation, although the increase in rotation was most evident between distances 1 and 2. No other significant interaction effects were found.

While Fig. 3 illustrates significant trends for inter-segmental trunk motions within this subject population, a great deal of inter-subject variability was also evident. No single subject displayed a movement pattern that was fully representative of the group means, although certain subjects deviated more from these means than others. Specific examples are provided below.

3.2.1. Movement toward targets in the sagittal plane

Fig. 4 illustrates the cumulative inter-segmental flexion patterns for three subjects, for a single trial toward an anteriorly placed target at distance 3. The pattern illustrated in Fig. 4A closely approximates the group average. The greatest motion occurs at the caudal levels, with relatively uniform movement occurring at the lower thoracic levels, and a total trunk flexion similar to the group mean. Fig. 4B illustrates a drastically different distribution of inter-segmental motion in flexion, with the greatest range at ULx and MLTx, and a total trunk flexion well below the group mean. A spike of flexion is also evident at LLx, near the point of peak trunk motion (also evident in the curves for the other trunk levels due to the summative nature of these curves), likely indicative of a thrust toward the target at peak motion rather than the continuous, smooth patterns seen in Fig. 4A. Finally, Fig. 4C illustrates a movement pattern with flexion at LLx well above the group average, relatively uniform flexion from ULx to MLTx, and extension at MUTx and UTx. This pattern also shows some unevenness around the peak of trunk motion, during which the relative distribution of motion between trunk levels is notably variable.

Despite this variability in the distribution of trunk flexion between levels, very little off-axis, coupled motion (side-bending and rotation) was observed during movements toward the anterior

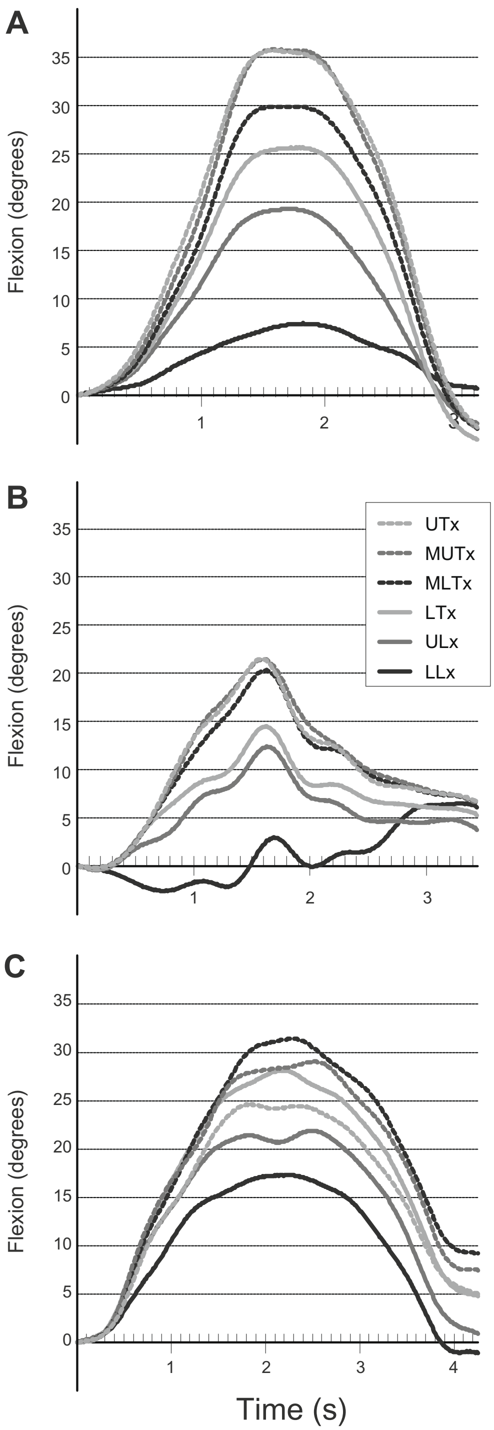

Fig. 4. Cumulative flexion motion patterns at each trunk level within the multi-segmental model, for three subjects, for a single trial toward an anteriorly placed target at distance 3. Cumulate motion is presented to each visual comparison, with the motion illustrated for each level representing the summed motion for that level with each more caudal level (e.g. the motion pattern illustrated for LTx is the summed motion for LTx, ULx and LLx).

targets. The mean side-bending and rotation angles during these movements, for the subject population, at all target distances and trunk levels, were less than 1.2° (equal to the approximated measurement accuracy of the model), although all subjects displayed a mean rotation and/or side-bend angle above 1.2° for at least one trunk level. Furthermore, only two subjects displayed a discernable pattern in these off-axis movements. One subject showed consistent side-bending at LTx for all movements toward the anterior target, regardless of target distance: distance 1, side-bend = −2.6°; distance 2, side-bend = −3.3°; distance 3, side-bend = −3.2°. A second subject demonstrated an increasing degree of left side-bend and right rotation at UTx with increasing target distance: distance 1, side-bend = −0.1°, rotation = 0.8°; distance 2, side-bend = −1.9°; rotation = 2.1°; distance 3, side-bend = −3.7°; rotation = 4.6°. This last value represents the largest off-axis movement observed for these sagittal plane movements, within this subject population.

3.2.2. Movements toward targets placed lateral to the sagittal plane

Post-hoc analysis of the ANOVA results for inter-segmental motion found no significant differences ($p > 0.85$) in the total range of trunk side-bending or rotation for movements toward targets placed 45° to the left and right of the sagittal plane (A-R vs. A-L), or for targets placed at 90° to the left and right of the sagittal plane (R vs. L).

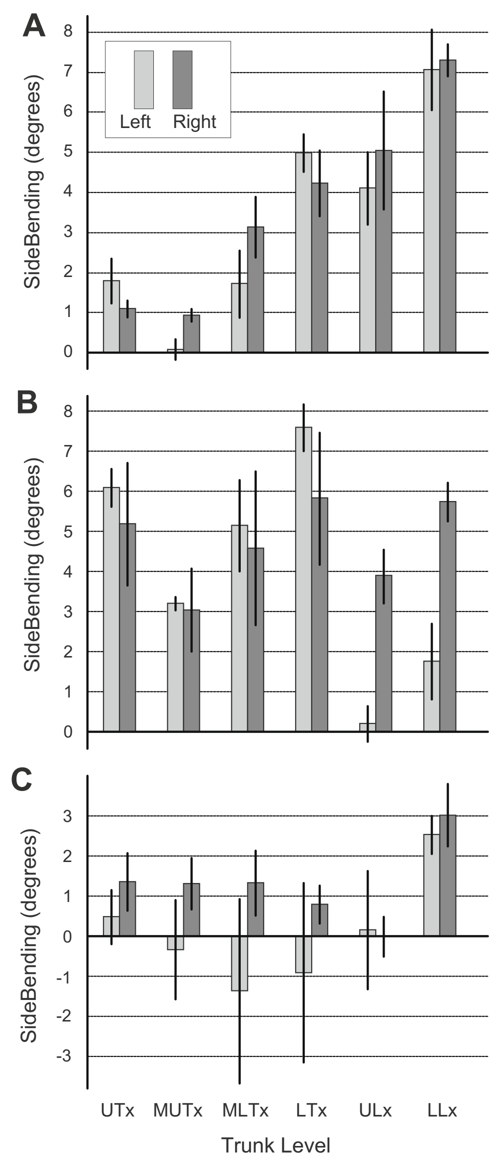

Fig. 5. Side-bending motion, at the point of peak trunk motion, at each trunk level within the multi-segmental model, for three subjects, during movement toward the targets placed in the frontal plane at distance 2. Bars represent the mean trunk motion over three trials. Error bars represent a range of plus or minus one standard deviation.

Please cite this article in press as: Preuss RA, Popovic MR. Three-dimensional spine kinematics during multidirectional, target-directed trunk movement in sitting. J Electromyogr Kinesiol (2009), doi:10.1016/j.jelekin.2009.07.005

Despite this statistical symmetry of motion across the subject population, the individual subjects displayed varying degrees of asymmetry during movements toward laterally placed targets. Fig. 5 illustrates the mean side-bending angle at peak trunk motion for three subjects; across the three trials for the left (L) and right (R) target directions (frontal plane), at distance 2. Fig. 5A illustrates values similar to the group mean, at each trunk level. A minimal degree of asymmetry is evident at each level, although these differences generally fall within the margin of potential measurement error (i.e. <1.2°). Fig. 5B shows values for a subject whose total side-bending motion was also similar to the group mean, but with an inter-segmental distribution that was notably different. Of particular note is the asymmetry of side-bending motion at the lumbar levels, which far exceeds the margin of measurement error, and the apparent compensation in the thoracic levels. Finally, Fig. 5C shows values for a subject whose inter-segmental and total trunk side-bending were drastically different from the group mean. Very little side-bending is evident at any trunk level during movement toward the frontal plane targets, such that the mean motion at all levels above LLx approached the margin of measurement error.

4. Discussion

The findings of the current study indicate that a multi-segmental analysis of spine motion during functional trunk movements may reveal complex, inter-segmental variations based on the requirements of the task, as well as differences in movement patterns between individual subjects.

4.1. Total trunk motion

Significant differences in total trunk flexion were found between the three kinematic models of spine motion, reflecting the differences in how these values were measured. The multi-segmental model (and to a lesser degree the Lumbar–Thoracic model) assessed the relative orientation of adjacent segments, while in the Whole-Trunk model motion was measured relative to the orientation of the sacrum. For movements in the sagittal plane (anterior target placement) this was not an issue, as the flexion axis (X-axis, Fig. 1) for all segment levels remained more or less parallel (coupled motions were minimal). When motion occurred in more than one plane, however, the relative orientation of the flexion axes at each spine level was altered, and the sum of the flexion measured at each level was no longer equal to the total measure taken about the flexion axis of the sacrum. The same was also true for movements about the other axes, although in the current study statistical differences were only found for flexion. Such differences in model segmentation, therefore, are important when interpreting the findings of any study examining the kinematics of the spine, and are discussed in greater detail below (Section 4.4).

As would be expected, the total trunk motion was also significantly affected by the target placement. Lateral target placements lead to a decrease in trunk flexion and an increase in side-bending and rotation (main effects of direction). Movements toward a more distally placed target, on the other hand, generally lead to an increase in trunk motion about all axes (main effects of distance). The latter, however, was somewhat more tempered, although still significant, for axial rotation than for the other spine motions. This likely reflects the instructions to the subjects to look at the target before beginning their movement toward it. While no specific instructions were given regarding how to turn (i.e. turn your head, turn your shoulders, etc.), a great deal of trunk rotation was typically evident prior to the subject initiating the movement toward the laterally placed targets. Much of the axial rotation observed, therefore, served to orient the subject's gaze in the direction of the target.

4.2. Inter-segmental trunk motion

The multi-segmental model of the trunk revealed complex motion patterns that cannot be adequately represented by measures of Whole-Trunk motion. Even for movements toward the anteriorly placed targets, an interaction effect between trunk level and target distance was evident. Specifically, the flexion pattern in the upper thoracic spine was notably different than at more caudal levels when target distance was increased (Fig. 3); likely in an effort to preserve spine length in order to reach the target. The variability in the amplitude of motion observed across this study population (Figs. 3 and 4) also suggests that the assumption of proportional motion across spine segments (Goodvin et al., 2006) would be of limited use for the assessment of individual patients.

Side-bending, and to a lesser degree axial rotation (Fig. 3), in the upper thoracic levels was proportionally small compared with reported values for the available segmental ranges of motion (Willems et al., 1996; McGill, 2002). Once again, this likely reflects the more functional nature of the target-directed task used in this study, which required the subject visually fix a target prior to movement, and to preserve spine length during movement in order to reach that target. The assumption of proportional motion across spine segments, therefore, appears to be of little practical utility for any but the simplest of trunk movements.

By far the most interesting observation with respect to inter-segmental motion, however, was in the altered distribution of movements between segments for the different target placements (interaction effect of level and direction), suggests complex and task-specific patterns of trunk motion. At LLx, for example, the distribution of segmental flexion changed dramatically for the different target placements (Fig. 3). As a decrease in the available range of flexion at this spine level, with concomitant axial rotation and side-bending, is unlikely (Pearcy, 1993), the most plausible explanation is that flexion at LLx would not functionally contribute to trunk motion in the frontal plane. At ULx, however, a great deal of flexion was observed for movement toward the targets placed to the left (L) and right (R), despite inadequate axial rotation below this level to orient this segment in the frontal plane. The observed flexion at this level, therefore, likely reflects a flattening of the lumbar lordosis, which when combined with side-bending and rotation can aid in elongating the spine toward the target.

Movement at LTx reflected a "transition" region between the lumbar and mid-thoracic levels, with both side-bending and flexion increasing relatively consistently with target distance, for all target directions. Motion patterns at the mid-thoracic levels (MLTx and MUTx), however, were notably different from those in the lumbar segments. Axial rotation was greatest at MLTx, allowing flexion above this level to make a greater contribution to movements outside the sagittal plane. As such, more flexion was observed at these levels for movements toward the more laterally placed targets. Motion at UTx, on the other hand, was generally negligible (approaching the range of measurement error), with the exception of axial rotation. This suggests that spine motion at this level was closely related to maintaining the orientation of the head and the effective length of the spine during these target-directed movements.

4.3. Individual subject variability

A secondary goal of this study was to assess the amount, and type, of variability of spine motion that would be observed in a healthy subject population. The participants in this study were young and healthy, with no prior history to suggest that their patterns of spine kinematics should represent abnormal or pathological motion patterns. Despite this, the motion patterns that were observed were highly variable across this relatively small subject population (Figs. 3–5).

Previous studies have also noted a great deal of variability in spine motion between healthy subjects. Gatton and Pearcy (1999), for example, examined the sequence in which flexion occurred in the lumbar spine across a variety of tasks, using a subject group that was comparable to the one in the current study. These authors identified four possible sequences of movement for lumbar flexion, but concluded that there was no dominant pattern of motion across their subject population, with the same subject often demonstrating different movement sequencing between tasks.

This "normal" variability, therefore, presents an obstacle to researchers and clinicians aiming to identify pathological patterns of motion in symptomatic patients, or "at risk" patterns of motion in asymptomatic individuals. Recent evidence suggests, however, that patients with low back pain may be classified based on the patterns of movement which induce symptoms (Van Dillen et al., 2003), and that patients with different classifications will demonstrate specific patterns of spine motion during standardized tasks (Gombatto et al., 2007; Van Dillen et al., 2007). In particular, the symmetry of motion appears to be important in this regard. Identifying symmetrical movement patterns, therefore, might also prove useful in identifying subjects at risk of developing low back pain. A similar approach could also be used to identify asymmetrical or aberrant movement patterns in patients with neuromuscular impairments following stroke or spinal cord injury, and used to guide clinical treatment.

The results of the current study indicate that the multi-segmental model can provide a useful tool to measure spine motion in three-dimensions, and to identify movement asymmetries, as differences in movement patterns and amplitudes between subjects and movement directions were routinely larger than the potential measurement error of the system (Figs. 4 and 5). Other observations, such as variability in motion patterns at the end range of movement (Fig. 4C) may also be clinically relevant, as even a minor loss of coordination at end-range flexion may lead to injury (Cholewicki and McGill, 1992; Preuss and Fung, 2005).

The findings of the current study must, however, be viewed in the context of the relatively small, mixed-gender sample population from which these data were obtained. This limits any generalization of these findings beyond this sample population, and, as such, these findings cannot be viewed as a normative database, or as representative of either a healthy male or female population. A much larger sampling would be required to determine what constitutes a "normal" movement pattern for male and female subjects, or at least a range of "normal" from which outliers could be viewed as "abnormal". Such an approach could then be used to develop a database of spine motion for functional or clinically important movements, in order to better identify abnormal or aberrant movement strategies. A similar approach has previously been used to establish databases for ranges of motion in the cardinal planes (Russell et al., 1993; Gracovetsky et al., 1995; Willems et al., 1996; Van Herp et al., 2000), often including off-axis coupled movements (Russell et al., 1993; Willems et al., 1996; Troke et al., 2001; Edmonston et al., 2008). Databases of end range of motion, however, have proven to be of limited clinical utility, as range of motion is only weakly correlated with disability in patients with low back pain (Sullivan et al., 2000), and is unlikely to be of primary importance in treating issues related to impaired neuromuscular control and coordination in other patient populations. The multi-segmental model used in this study, therefore, provides the means to move beyond the cardinal planes of movement, and beyond measure of end range of motion, in the quantitative assessment of segmental spine motion.

4.4. Considerations for multi-segmental modelling of spine motion

The data presented in this study support the notion that increased segmentation of the kinematic model used to assess trunk motion will improve the utility of those measurements. Practical limitations do exist, however. The size of the skin-mounted sensors used with electromagnetic (Gatton and Pearcy, 1999) and inertial (Lee et al., 2003) systems may limit the placement of these relative to the individual vertebrae, although very small sensors capable of measuring motion in six degrees-of-freedom are now available with certain systems. The more important consideration with all systems, therefore, is the signal to noise ratio that is present in these measurements (i.e. the magnitude of the measured values relative to the accuracy with which these variables of interest can be represented). The main considerations here are the accuracy of the sensor itself and the movement of the skin-mounted sensor(s) relative to the underlying vertebrae (Cappozzo et al., 1997). Motion of an individual vertebral motion segment will rarely exceed 10° (McGill, 2002) at end range. Functional spine movements, on the other hand, rarely approach these values. The accuracy with which individual vertebral motion can be tracked using surface sensors, therefore, is suspect. Even optoelectronic systems, whose markers can be very small (<10 mm), and whose accuracy can be very high, may not allow good measurements of individual vertebral kinematics. These systems require at least three markers to track the motion of any rigid body in three-dimensions, and the measured position of all three markers is subject to a degree of error based on factors such as the calibration residual of the system. Furthermore, as segmental motion is calculated as the motion of one segment relative to another, the error associated with the measured orientation of each segment will play a factor. In the current study, for example, calibration residuals were below 0.5 mm, roughly representing the potential error in the measured position of each marker. With a marker spacing of 100 mm for each marker triad, this represents an accuracy of $\sim$0.6° for the orientation of each segment. The orientation of one segment relative to another, therefore, can only be considered accurate to $\sim$1.2°, without consideration for marker movement relative to the underlying skeletal structures. Tracking individual vertebral motion using a similar system would require a much tighter marker placement (Andreoni et al., 2005; Ciavarro et al., 2006), which would decrease the accuracy with which these orientations could be represented, while at the same time decreasing the magnitude of the measured movements.

The issue of relative skin motion may be negated using invasive approaches such as percutaneous screws (Lund et al., 2002), although this approach has clear practical and ethical limitations. In addition, it is uncertain whether the presence of such surgical hardware will mechanically alter vertebral kinematics, due to mechanical forces at the screw – skin interface, or affect neuromuscular control and coordination. Imaging techniques such as X-ray (Pearcy and Tibrewal, 1984; Abbott et al., 2006) and MRI (Kulig et al., 2007) can provide static representations of vertebral position, but their application for movement studies is limited. Video fluoroscopy (Cholewicki et al., 1991) presents an alternative, but has issues related to radiation exposure, availability of equipment and subject positioning. Skin mounted motion capture, therefore, remains the most viable approach for most studies of trunk and spine motion (approaches such as raster stereography (Schulte et al., 2008) may also be viable alternatives for some clinical applications). The multi-segmental model presented in this study provides a viable approach when the measurements are interpreted within the context of the above limitations.

Please cite this article in press as: Preuss RA, Popovic MR. Three-dimensional spine kinematics during multidirectional, target-directed trunk movement in sitting. J Electromyogr Kinesiol (2009), doi:10.1016/j.jelekin.2009.07.005

Another issue that must be addressed in future studies relates to the calibration of the zero position for these measurements (as opposed to the calibration of the system itself). The kinematic model of spine motion presented in this study represents the relative motion of spine segments, with the zero position chosen as the upright sitting posture naturally adopted by the subjects at the start of the measurement. Such an approach, however, is less viable for other patient populations where the subjects may not be capable of adopting a neutral spine posture. A system to measure the initial static spine posture should therefore be adopted in future studies, in order to provide a reliable value from which relative motion can be determined.

4.5. Conclusion

The data presented in this study indicate that the degree of segmentation of the kinematic model of the spine will affect the total trunk motion measured during multi-planar movements. Furthermore, a multi-segmental analysis appears to have several advantages, providing improved insight into the complex, task dependent motions of the trunk, and the often uneven distribution of that motion between spine levels. Motion patterns were seen to differ between subjects even in the absence of pathology. This variability, and the ability of the multi-segmental kinematic model of the spine to differentiate between individual motion patterns, suggests that detailed, multi-segmental assessment of spine motion is necessary to fully understand spine kinematics during movement, and may be beneficial to the understanding of movement-related pathologies in the trunk.

Acknowledgements

This work was supported by the Canadian Institutes of Health Research (No. 129179), the Natural Sciences and Engineering Research Council of Canada, the Ministry of Health and Long Term Care in Ontario, and the Toronto Rehabilitation Institute. Richard Preuss is supported by a fellowship from the Fonds de la recherche en santé du Québec (FRSQ). We would like to thank Dr. Joyce Fung, and the Jewish Rehabilitation Hospital Research Site of the Centre for Interdisciplinary Research in Rehabilitation (CRIR), for the use of equipment and laboratory space for the acquisition of these data. The authors are not aware of any conflicts of interest related to these data.

References

Abbott J, Fritz J, McCane B, Shultz B, Herbison P, Lyons B, et al. Lumbar segmental mobility disorders: comparison of two methods of defining abnormal displacement kinematics in a cohort of patients with non-specific mechanical low back pain. BMC Musculoskel Disord 2006;7. doi: 10.1186/1471-2474-7-45.

Allison G, Fukushima S. Estimating three-dimensional spinal repositioning error: the impact of range, posture, and number of trials. Spine 2003;28:2510–6.

Andreoni G, Negrini S, Ciavarro G, Santambrogio G. ZooMS: a non-invasive analysis of global and metameric movement of the lumbar spine. Eur J Med Phys 2005;41:7–16.

Cappozzo A, Cappello A, Della Croce U, Pensalfini F. Surface-marker cluster design criteria for 3-D bone movement reconstruction. IEEE Trans Biomed Eng 1997;44:1165–74.

Cholewicki J, McGill S. Lumbar posterior ligament involvement during extremely heavy lifts estimated from fluoroscopic measurements. J Biomech 1992;25:17–28.

Cholewicki J, McGill S, Wells R, Vernon H. Method for measuring vertebral kinematics from videofluoroscopy. Clin Biomech 1991;6:73–8.

Ciavarro G, Andreoni G, Negrini S, Santambrogio G. Functional assessment of the lumbar spine through the optoelectronic ZooMS system: clinical application. Eur Medicophys 2006;42:135–43.

Edmonston S, Aggerholm M, Elfving S, Flores N, Ng C, Smith R, et al. Influence of posture on the range of axial rotation and coupled lateral flexion of the thoracic spine. Journal Manip Physiol Ther 2008;30:193–9.

Gatton M, Pearcy M. Kinematics and movement sequencing during extension of the lumbar spine. Clin Biomech 1999;14:376–83.

Gombatto S, Collins D, Sahrmann S, Engsberg J, Van Dillen L. Patterns of lumbar region movement during trunk lateral bending in 2 subgroups of people with low back pain. Phys Ther 2007;87:441–54.

Goodvin C, Park E, Huang K, Sakaki K. Development of a real-time three-dimensional spinal motion measurement system for clinical practice. Med Biol Eng Comput 2006;44:1061–75.

Gracovetsky S, Newman N, Pawlowsky M, Lanzo V, Davey B, Robinson L. A database for estimating normal spinal motion derived from non-invasive measurements. Spine 1995;20:1036–46.

Hsu C, Chang Y, Chou W, Chiou C, Chang W, Wong C. Measurement of spinal range of motion in healthy individuals using an electromagnetic tracking device. J Neurosur Spine 2008;8:135–42.

Kulig K, Powers C, Landel R, Chen H, Fredericson M, Guillet M, et al. Segmental lumbar mobility in individuals with low back pain: in vivo assessment during manual and self-imposed motion using dynamic MRI. BMC Musculoskel Disord 2007;8.

Lee R, Laprade J, Fung E. A real-time gyroscopic system for three-dimensional measurement of lumbar spine motion. Med Eng Phys 2003;25:817–24.

Lee R. Kinematics of rotation mobilisation of the lumbar spine. Clin Biomech 2001;16:481–8.

Lund T, Nydegger T, Schlenzka D, Oxland T. Three-dimensional motion patterns during active bending in patients with chronic low back pain. Spine 2002;27:1865–74.

McGill S. Low back disorders: evidence-based prevention and rehabilitation. Champaign: Human Kinetics Publishers; 2002.

McGregor A, Cattermole H, Hughes S. Global spinal motion in subjects with lumbar spondylolysis and spondylolisthesis: does the grade or type of slip affect global spinal motion? Spine 2001;26:282–6.

Newcomer K, Laskowski E, Yu B, Johnson J, An K. The effects of a lumbar support on repositioning error in subjects with low back pain. Arch Phys Med Rehabil 2001;82:906–10.

Pearcy M, Hindle R. New method for the non-invasive three-dimensional measurement of human back movement. Clin Biomech 1989;4:73–9.

Pearcy M, Tibrewal S. Axial rotation and lateral bending in the normal lumbar spine measured by three-dimensional radiography. Spine 1984;9:582–7.

Pearcy M. Twisting mobility of the human back in flexed postures. Spine 1993;18:114–9.

Preuss R, Fung J. Can acute low back pain result from segmental spinal buckling during sub-maximal activities? A review of the current literature. Manual Ther 2005;10:14–20.

Preuss R, Fung J. Musculature and biomechanics of the trunk in the maintenance of upright posture. J Electromyogr Kines 2008;18:815–28.

Russell P, Pearcy M, Unsworth A. Measurement of the range and coupled movements observed in the lumbar spine. Brit J Rheum 1993;32:490–7.

Schulte T, Hierholzer E, Boerke A, Lerner T, Liljenqvist U, Bullman V, et al. Raster stereography versus radiography in the long-term follow-up of idiopathic scoliosis. J Spinal Disord Tec 2008;21:23–8.

Sullivan M, Shoaf L, Riddle D. The relationship of lumbar flexion to disability in patients with low back pain. Phys Ther 2000;80:240–50.

Swinkels A, Dolan P. Regional assessment of joint position sense in the spine. Spine 1998;23:590–7.

Troke M, Moore A, Maillardet F, Hough A, Cheek E. A new, comprehensive normative database of lumbar spine ranges of motion. Clin Rehabil 2001;15:371–9.

Van Dillen L, Sahrmann S, Norton B, Caldwell C, McDonnell M, Bloom N. Movement system impairment-based categories for low back pain: stage 1 validation. J Orthop Sports Phys Ther 2003;33:126–42.

Van Dillen L, Gombatto S, Collins D, Engsberg J, Sahrmann S. Symmetry of timing of hip and lumbopelvic rotation motion in 2 different subgroups of people with low back pain. Arch Phys Med Rehabil 2007;88:351–60.

Van Herp G, Rowe P, Salter P, Paul J. Three-dimensional lumbar spinal kinematics: a study of range of movement in 100 healthy subjects aged 20 to 60+ years. Rheumatology 2000;39:1337–40.

Willems J, Jull G, Ng J. An in vivo study of the primary and coupled rotations of the thoracic spine. Clin Biomech 1996;11:311–6.

Richard Preuss PhD PT holds a masters degree in Kinesiology from the University of Waterloo (Waterloo, Canada) and a PhD in Rehabilitation Science from the School of Physical and Occupational Therapy at McGill University (Montreal, Canada). He is currently a post-doctoral fellow in the Rehabilitation Engineering Laboratory at the Toronto Rehabilitation Institute (Toronto, Canada).

Please cite this article in press as: Preuss RA, Popovic MR. Three-dimensional spine kinematics during multidirectional, target-directed trunk movement in sitting. J Electromyogr Kinesiol (2009), doi:10.1016/j.jelekin.2009.07.005

Milos R. Popovic received his PhD degree in mechanical engineering from the University of Toronto, Ontario, Canada in 1996, and the Dipl. Electrical Engineer degree from the University of Belgrade, Yugoslavia in 1990. He is the Toronto Rehab Chair in Spinal Cord Injury Research. He is also an Associate Professor in the Institute of Biomaterials and Biomedical Engineering at the University of Toronto, as well as Senior Scientist and the Activity Team Leader at the Toronto Rehabilitation Institute. Both institutions located in Toronto, Ontario, Canada.

He joined the Institute of Biomaterials and Biomedical Engineering and the Toronto Rehab in 2001. From 1997 until 2001 he led the Rehabilitation Engineering Team at the Swiss Federal Institute of Technology (ETH) and the Paraplegic Center of the University Hospital Balgrist, both in Zurich, Switzerland. From 1996 until 1997, he worked for AlliedSignal Aerospace Canada Inc. in Toronto, Canada.

His fields of expertise are functional electrical stimulation, neuro-rehabilitation, modeling and control of linear and non-linear dynamic systems, robotics, power systems, signal processing, and safety analysis. His interests are in the areas of neuro-rehabilitation, physiological control systems, assistive technology, and brain machine interfaces. In 1997, together with Dr. Thierry Keller he received the Swiss National Science Foundation Technology Transfer Award – 1st place. In 2008, he was awarded the Engineering Medal for Research and Development from the Professional Engineers of Ontario and Ontario Society of Professional Engineers. He is also one of the co-founders of the Canadian National Spinal Cord Injury Conference, established in 2004.