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Manuscript Title:

"A 3-Dimensional Rigid Cluster Thorax Model for Kinematic Measurements during Gait"

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Abstract

The trunk has been shown to work as an active segment rather than a passenger unit during gait and it is felt that trunk kinematics should be given more consideration during gait assessment. While 3-dimensional assessment of the thorax with respect to the pelvis and laboratory can provide a comprehensive description of trunk movement, the majority of existing 3-D thorax models demonstrate shortcomings such as the need for multiple skin marker configurations, difficult landmark identification and practical issues for assessment on female subjects. A small number of studies have used rigid cluster models to quantify thorax movement, however the models and points of attachment are not well described and validation rarely considered. The aim of this study was to propose an alternative rigid cluster 3-D thorax model to quantify movement during gait and provide validation of this model. A rigid mount utilising active markers was developed and applied over the 3rd thoracic vertebra, previously reported as an area of least skin movement artefact on the trunk. The model was compared to two reference thorax models through simultaneous recording during gait on 15 healthy subjects. Excellent waveform similarity was demonstrated between the proposed model and the two reference models (CMC range 0.962 to 0.997). Agreement of discrete parameters was very-good to excellent. In addition, ensemble average graphs demonstrated almost identical curve displacement between models. The results suggest that the proposed model can be confidently used as an alternative to other thorax models in the clinical setting.

1. Introduction:

The trunk acts as an active segment rather than a passive unit during gait (Armand et al., 2014, Leardini et al., 2009). Plantarflexor weakness, hip adductor weakness and hip extensor weakness can all result in compensatory trunk patterns and consequently it has been suggested that trunk kinematics should be considered an important part of the pathological gait assessment (Gutierrez et al., 2003, Lamoth et al., 2002). Methods for modelling the trunk range in complexity, depending on the movement of interest, with trunk kinematics often described by tracking a combination of skin surface markers placed directly on the thorax segment (Gutierrez et al., 2003, Nguyen and Baker, 2004, Romkes et al., 2007, Su et al., 1998). A number of drawbacks exist when using this approach. Skin surface markers require experienced clinicians for palpation and localisation of anatomical landmarks, although there is still room for error regardless of the experience of the clinician (Armand et al., 2014). For pathological groups such as Cerebral Palsy this can be made all the more difficult as cooperation may be an issue when applying multiple marker sets. Many thorax models require a marker on the Xypoid Process (XP). Issues regarding the practicality and invasiveness of accurately applying this marker in females have been previously highlighted (Armand et al., 2014). Skin surface markers are also susceptible to Skin Movement Artefact (SMA), where soft tissue moves over the underlying bone. As an alternative to the skin surface marker approach, we propose a rigid marker cluster model that attaches to a single point on the thorax. Few studies have used rigid marker clusters for measuring thorax movement during gait and where they have been used the specific point of attachment is often not reported (Houck et al., 2006, Krebs et al., 1992, Wu et al., 2004). When placed at the appropriate point, a rigid cluster has the potential to address many of the limitations of the skin surface marker approach and provide a better fit for the clinical assessment. Consequently, there is a clinical need for such a model. Following from this, the aim of this study is to describe and provide validation of a rigid cluster model to quantify thorax movement during gait.

2. Materials and Methods:

2.1 Subjects

Fifteen healthy subjects participated in the study: 9 male, 6 female, aged 6 to 18 years. Informed written consent was obtained from all participants and from their parents when legally minor. The study was approved by the Central Remedial Clinic’s Ethical Committee.

2.2 Thorax Model

The thorax model of this research, the Central Remedial Clinic Thorax Model (CRCTM), was developed using custom scripts in Matlab 8.1.0.604 (The MathWorks, Natick, Massachusetts, USA). The CRCTM is further development of a model used previously in our laboratory for measuring functional movements at the low back (Rice et al., 2004). Markers were placed on a rigid mount attached to the thorax at the level of T3 (3rd Thoracic Vertebra). T3 has been previously highlighted to lie within the area of least skin movement artefact during active movement of the trunk (Rice et al., 2002). The mount was made of lightweight plastic with a small rectangular base that attached to the skin using double sided sticky tape (Fig.1). The mount sits proud of the back so markers are not obscured by shoulder or arm movement. Three active markers were attached to the mount. The centre lines of the mount's longitudinal and transverse axes were marked and aligned with the vertical axis of the spine and the centre of T3. The Z-axis of the model was defined using two markers along the base of the mount. Positive Z-axis was defined as m2 to m1 (Fig.2). The X-axis was defined using a Gram-Schmidt procedure incorporating m3 and the Z-axis with positive X-direction forward through the body (Fig.2). The Y-axis was defined as the vector product of the X-axis and Z-axis.

The CRCTM angles were calculated according to International Society of Biomechanics (ISB) recommendations as the rotation between (1) the thorax axes system and the pelvic axes system and (2) the thorax axes system and the laboratory. The pelvic axes system was as previously described (Newman et al., 2007). The laboratory coordinate system was defined with the x-axis pointing forward along the laboratory walkway, the y-axis pointing in a medio-lateral direction and the z-axis in a vertical direction. Subjects walked along the x-axis of the laboratory. The Cardanic sequence for angular decomposition was Y-X-Z.

2.3 Validation of the Model

For validation purposes, the CRCTM was compared with two reference thorax models from the literature. Model 1 (ISB) was defined according to anatomical landmarks as reported by the ISB to define the thorax segment (Wu et al., 2005). The anatomical landmarks are the 7th cervical vertebra (C7), 8th thoracic vertebra (T8), Incisura Jugularis (IJ) and XP (Fig.3). It is the role of individual researchers to relate tracking markers to these points. For the purposes of this study, skin surface markers were attached directly to these points. Model 2 (Armand) was defined using an "optical and minimal" skin marker set (Armand et al., 2014). Markers were placed directly at IJ, 2nd thoracic vertebra (T2), and T8. Thorax rotations for both models were defined according to ISB recommendations (Fig.3). For comparison purposes, the relationship between ISB and Armand models was also compared.

2.4 Data Collection

The 3-dimensional kinematic analysis was performed using the CODA cx1 active marker system (Charnwood Dynamics Ltd., Leicestershire). Data for all three models were captured simultaneously (Fig.3). Due to the rigid nature of the thorax and the duplication of data during the double support phase of gait, only one side of data (left) is reported for the purposes of this study. Subjects were asked to walk at a self selected pace with two representative files recorded and averaged per subject. A static standing trial was also recorded for each subject. Final parameters were calculated as the thorax angle (at each point in the gait cycle) minus the mean of the static standing angle for each model. The purpose of this was to perform a "zeroing effect" and account for the offset due to different definitions of anatomical axes (Collins et al., 2009).

2.5 Data Analysis

An alternative formulation of the coefficient of multiple correlation (CMC) was used to assess waveform similarity across the gait cycle (Ferrari et al., 2010). This approach is recommended for the calculation of CMCs of waveforms measured simultaneously by different protocols (Roislien et al., 2012). A CMC > 0.9 was chosen as the minimum acceptable value to demonstrate high similarity. Bland and Altman 95% Limits of Agreement (LoA) were calculated for peak and range parameters of each angle to assess agreement between models. Ensemble averages of thorax angles were visually analysed for deviations across the three thorax models. CMC values were calculated in Matlab 8.1.0.604 (The MathWorks, Natick, Massachusetts, USA), while Bland and Altman results and ensemble average graphs were calculated in Microsoft Excel.

Results:

3.1 Waveform Similarity

Excellent waveform similarity as measured by the CMC can be seen between all 3 sets of models in all 3 planes for calculations both with respect to the lab and pelvic co-ordinates frames (Table 1). CMC values ranged from 0.962 to 0.999. The highest level of similarity between CRCTM and Armand was for thorax flexion (w.r.t pelvis) (CMC = 0.997). The lowest waveform similarity values were recorded between CRCTM and ISB for thorax rotation (w.r.t lab) (CMC = 0.966), and between CRCTM and ISB for thorax flexion (w.r.t lab) (CMC = 0.962).

3.2 Limits of Agreement (LoA)

LoA for peak kinematic parameters were high overall with similar agreement demonstrated between CRCTM and Armand and CRCTM and ISB (Table 2). LoA ranged from -3.01° to 3.60° for thorax side flexion (w.r.t pelvis) to -5.15° to 6.07° for thorax flexion (w.r.t lab) between CRCTM and Armand. When CRCTM was compared to ISB, LoA ranged from – 3.62° to 3.50° for thorax side flexion (w.r.t lab) to -3.92° to 7.22° for thorax rotation (w.r.t pelvis). LoA for range kinematic parameters were high and similar both between CRCTM and Armand and CRCTM and ISB (Table 3). A high level of agreement was present between ISB and Armand models for both peak and range parameters. Bland and Altman plots are available in Supplementary Data.

3.3 Ensemble Averages

Ensemble average graphs show almost identical curve displacements for each angle when comparing CRCTM and Armand (Fig. 4) and CRCTM and ISB (Fig. 5). Thorax rotation (w.r.t lab and pelvis) demonstrated a slightly higher standard deviation band for the CRCTM when compared to both reference models, with a small deviation from reference model mean value evident during the swing phase of gait (Figs. 4 & 5).

Discussion:

The CRCTM has a number of advantages over other thorax models. While a reliability analysis was not part of this study, the position of T3 is easily identifiable in the majority of subjects thus potentially reducing the error associated with the palpation of landmarks. The rigid cluster can be easily attached which can be particularly useful when patient cooperation is an issue. The rigid mount stands proud of the thorax so as not to be obscured by arm movements thus improving marker visibility. There is no need for the XP marker thus avoiding any practical and potentially embarrassing issues for assessment on females and although not tested in this study, the model has the potential to be less susceptible to SMA error as it is positioned on an area of least skin movement on the trunk (Rice et al., 2002). In relation to validation of the CRCTM, excellent waveform similarity was demonstrated when compared to both reference models, with CMC values all greater than 0.962 (Table 1). This suggests that the CRCTM measures almost identical movements to both reference models.

When considering LoA, it has been suggested that acceptable LoA are matter of clinical judgement (Bland and Altman, 1986). For the purposes of this study, the LoA and ensemble average graphs are considered in union. LoA for peak kinematic parameters are closest between the two reference models (ISB – Armand) (Table 2). This is evident in the ensemble average graphs where mean and standard deviation bands are practically identical (Fig.6). When CRCTM is compared to

Armand, the mean difference between models is low in all 3 planes (0.18^{o} – 1.71^{o}) with wider LoA most evident for thorax rotation w.r.t the lab (range 9.53^{o}) and pelvis (range 10.67^{o}). Similar findings are present between CRCTM and ISB. LoA for range kinematic parameters demonstrate a similar trend to peak parameters (Table 2). As the technical axes system of the CRCTM is not based on the anatomical axes system of the thorax, the potential exists for kinematic crosstalk where axial rotations around one axis are misinterpreted as occurring around another axis (Baker et al., 1999, Rivest, 2005). The reported differences between the CRCTM and reference models might be as a consequence of this. It is also possible that wobble error, due to oscillations of the mount during periods of higher accelerations of the thorax, may contribute somewhat to the reported differences, most evident for CRCTM thorax rotation compared to both reference models during the swing phase of gait (Figs.4 & 5). Future studies are necessary to test the CRCTM in activities where larger accelerations of the thorax occur, such a cutting manoeuvres or running.

A limitation of the “zeroing process”, used to account for different axes systems of the CRCTM and reference models, is the potential to mask alignment issues such as kyphosis. For the purposes of this study, data were collected on normal subjects with no obvious spinal deformities. However, on subjects where kyphosis is an issue, the axes systems of CRCTM and the reference models may be altered depending on the vertebral levels at which the kyphosis occurs. This alignment issue is a limitation of all models, including the current reference standard. The validity of three-dimensional trunk kinematics in people with spinal deformities has not, to our knowledge, been tested with any of the existing models, and is an important area for future study.

When considering the CRCTM for use during gait, the question presents whether the differences measured by the CRCTM are small enough to be considered insignificant from a clinical point of view. The mean differences between CRCTM and reference models are all below 3^{o} (absolute difference) for peak and range parameters (Tables 2 and 3). Waveform similarity was excellent for all angles and while LoA for thorax rotation are wide, the mean CRCTM angle remains close to both reference model mean values and well within the ± 1 SD band. With this in mind, and in the absence of a single measure to define an acceptable clinically meaningful difference between models, we conclude that the recorded differences are not large enough to be considered clinically meaningful. Consequently, we conclude that the proposed model can be confidently used as an alternative to other thorax models in the clinical setting.

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Conflict of interest statement

None of the authors had any financial or personal conflict of interest with regard to this study.

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Table.1 Alternative CMC values averaged over 15 subjects. Due to the simultaneous measurement of all 3 protocols and assumptions with respect to the rigid nature of the thorax segment, a CMC > 0.90 was chosen as the minimum acceptable value to demonstrate high similarity between waveforms**.**

CMC	CRC – Armand		CRC - ISB		ISB - Armand	
	Mean	SD	Mean	SD	Mean	SD
Thorax Flex (w.r.t Lab)	0.962	0.110	0.990	0.016	0.991	0.020
Thorax Side Flex (w.r.t Lab)	0.983	0.024	0.981	0.029	0.993	0.013
Thorax Rotation (w.r.t Lab)	0.991	0.014	0.966	0.111	0.985	0.040
Thorax Flex (w.r.t Pel)	0.997	0.004	0.994	0.014	0.999	0.001
Thorax Side Flex (w.r.t Pel)	0.982	0.041	0.978	0.043	0.997	0.004
Thorax Rotation (w.r.t Pel)	0.988	0.021	0.986	0.020	0.998	0.004

Table.2 Bland and Altman 95% Limits of Agreement (LoA) for peak kinematic parameters between CRCTM and Armand, CRCTM and ISB and ISB and Armand models (degrees).

Parameter	CRC - Armand			CRC - ISB			ISB - Armand		
	Bland- Altman 95% LoA			Bland- Altman 95% LoA			Bland- Altman 95% LoA		
	D	SD(D)	95% LoA	D	SD(D)	95% LoA	D	SD(D)	95% LoA
Thorax Flex (w.r.t Lab)	0.46	2.81	-5.15 to 6.07	-0.17	1.93	-4.03 to 3.69	0.64	1.22	-1.80 to 3.07
Thorax Side Flex (w.r.t Lab)	0.18	1.59	-3.01 to 3.37	-0.06	1.77	-3.62 to 3.50	0.24	0.93	-1.66 to 2.11
Thorax Rotation (w.r.t Lab)	0.85	2.38	-3.91 to 5.62	0.87	2.37	-3.88 to 5.61	-0.02	0.64	-1.29 to 1.26
Thorax Flex (w.r.t Pel)	0.65	2.77	-4.89 to 6.19	0.00	1.91	-3.83 to 3.83	0.65	1.14	-1.64 to 2.94
Thorax Side Flex (w.r.t Pel)	0.30	1.65	-3.01 to 3.60	0.51	1.78	-3.05 to 4.07	-0.22	1.02	-2.25 to 1.81
Thorax Rotation (w.r.t Pel)	1.71	2.67	-3.62 to 7.05	1.65	2.79	-3.92 to 7.22	0.06	0.74	-1.42 to 1.55

Table.3 Bland and Altman 95% Limits of Agreement (LoA) for range (Max – Min) kinematic parameters between CRCTM and Armand, CRCTM and ISB and ISB and Armand models (degrees).

Parameter	CRC - Armand			CRC - ISB			ISB - Armand		
	Bland- Altman 95% LoA			Bland- Altman 95% LoA			Bland- Altman 95% LoA		
	D	SD(D)	95% LoA	D	SD(D)	95% LoA	D	SD(D)	95% LoA
Thorax Flex (w.r.t Lab)	-0.57	0.65	-1.88 to 0.74	-0.66	0.61	-1.87 to 0.55	0.09	0.37	-0.65 to 0.82
Thorax Side Flex (w.r.t Lab)	-3.00	1.28	-2.86 to 2.26	-0.64	0.68	-2.01 to 0.72	0.34	0.87	-1.38 to 2.08
Thorax Rotation (w.r.t Lab)	-1.38	2.05	-5.48 to 2.71	-1.55	2.46	-6.47 to 3.37	0.17	0.69	-1.21 to 1.55
Thorax Flex (w.r.t Pel)	-0.52	0.73	-1.97 to 0.93	-0.65	0.72	-2.08 to 0.79	0.13	0.45	-0.77 to 1.02
Thorax Side Flex (w.r.t Pel)	-0.79	1.09	-2.97 to 1.38	-0.23	1.05	-2.33 to 1.87	-0.56	0.80	-2.17 to 1.05
Thorax Rotation (w.r.t Pel)	1.03	2.08	-3.14 to 5.19	0.80	2.14	-3.48 to 5.08	0.23	0.51	-0.80 to 1.25

Figure Legends

Figure 1: Position of the CRCTM on a normal subject. The rigid cluster is made of lightweight plastic with a small rectangular base that attached to the skin using double sided sticky tape. The mount sits proud of the back so markers are not obscured by shoulder or arm movement.

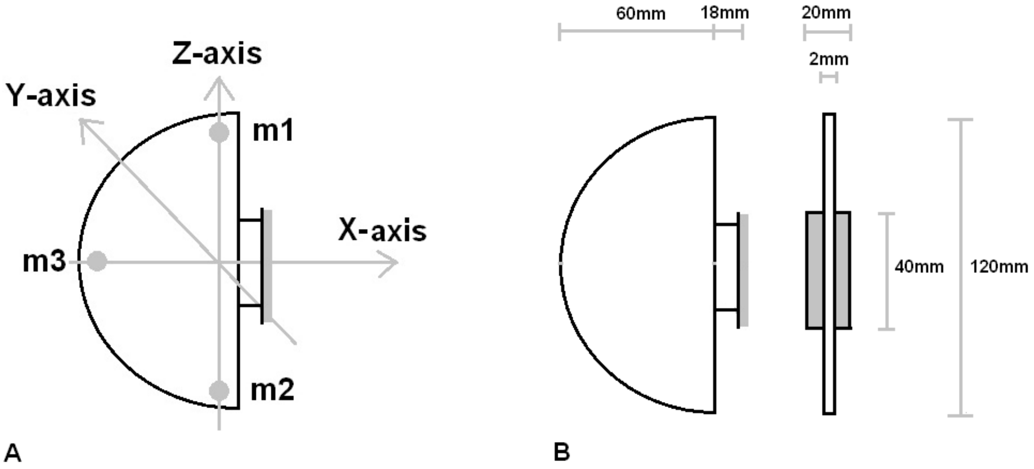
Figure 2 Schematic and dimensions of the thorax mount and the corresponding axes of the mathematical model. The Z-axis is defined by the vector between Marker 2 (M2) and Marker 1 (M1). The X-axis is defined as the vector between Marker 3 (M3) and the mid-point of M2 and M3. A Gram-Schmidt orthogonal procedure is used to define the Y-axis.

Figure 3: A stick figure diagram of all three thorax models in situ. Model 1 (ISB) defined using ISB recommendations, with markers placed directly at C7, T8, IJ and XP. Model 2 (Armand) defined using an “optical and minimal” skin marker set (Armand et al., 2013), with markers placed directly at IJ, T2 and T8. Model 3 (CRCTM) placed directly at T3 and aligned with the vertical axis of the spine.

Figure 4: CRCTM compared to Armand. Thorax kinematic curves for one gait cycle averaged over 15 normal subjects. Mean static standing angle deducted from walking trials to account for the offset due to different definitions of anatomical axes. CRCTM - grey dashed line (mean), grey band (± 1 SD). Armand- black line of circles (mean), solid black lines (± 1SD).

Figure 5: CRCTM compared to ISB. Thorax kinematic curves for one gait cycle averaged over 15 normal subjects. Mean static standing angle deducted from walking trials to account for the offset due to different definitions of anatomical axes. CRCTM - grey dashed line (mean), grey band (± 1 SD). ISB- heavy solid black line (mean), light solid black lines (± 1SD).

Figure 6: ISB compared to Armand. Thorax kinematic curves for one gait cycle averaged over 15 normal subjects. Mean static standing angle deducted from walking trials to account for the offset due to different definitions of anatomical axes. ISB - heavy solid black line (mean), light solid black lines (± 1SD). Armand - black circles (mean), grey band (± 1 SD).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m1
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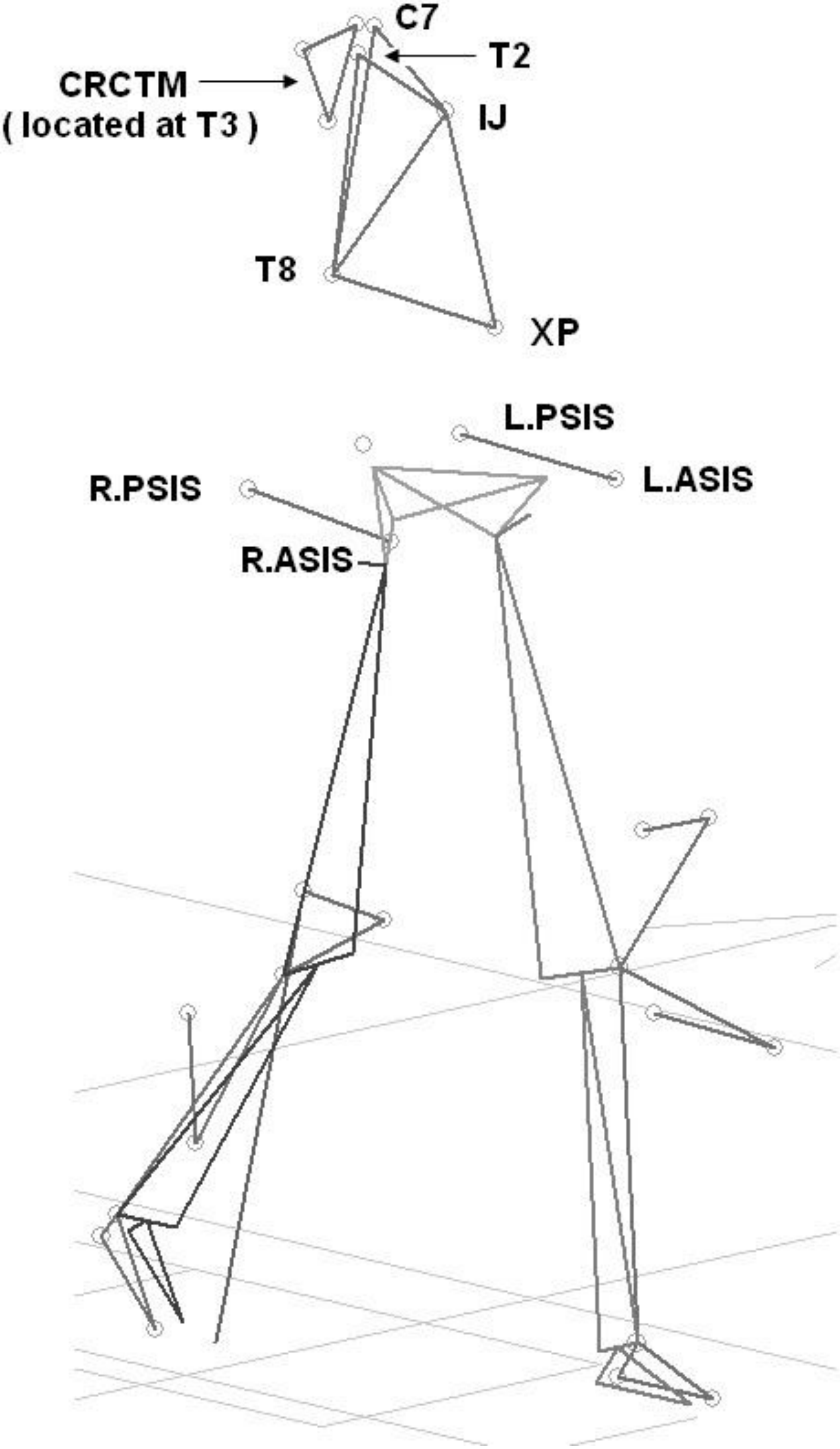
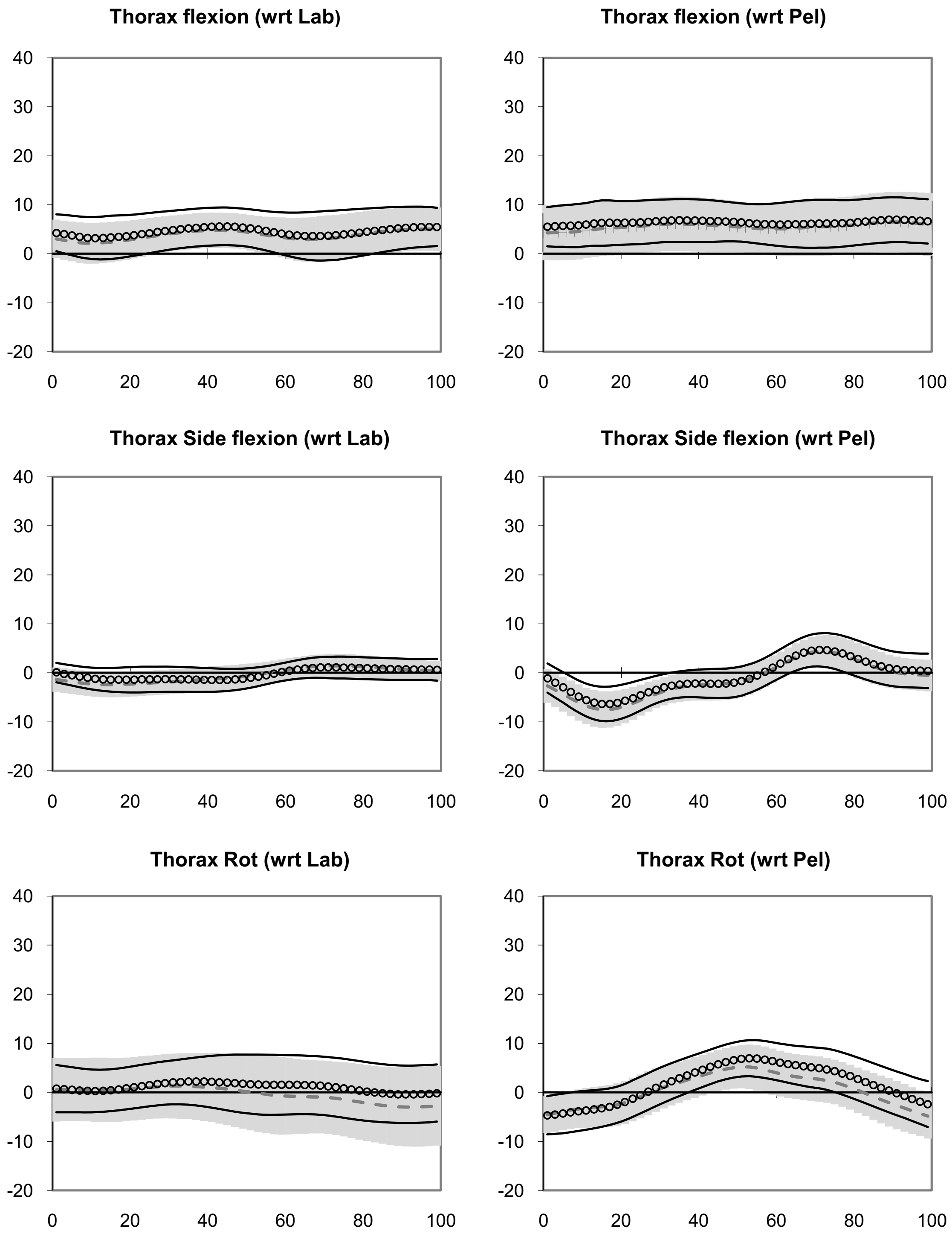

C7
T2
CRCTM
(located at T3)
IJ
T8
XP
L.PSIS
L.ASIS
R.PSIS
R.ASIS


Thorax flexion (wrt Lab)
Thorax flexion (wrt Pel)
Thorax Side flexion (wrt Lab)
Thorax Side flexion (wrt Pel)
Thorax Rot (wrt Lab)
Thorax Rot (wrt Pel)
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30
20
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0
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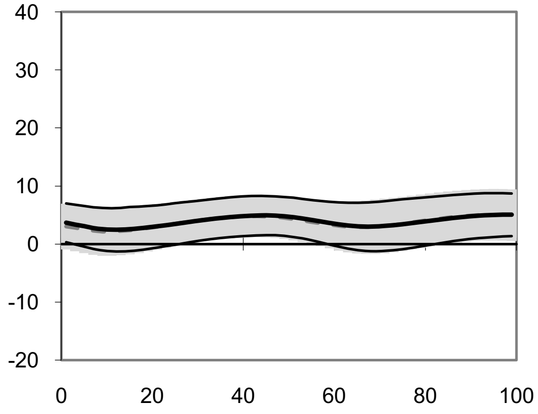
-20
0
20
40
60
80
100

Thorax flexion (wrt lab)



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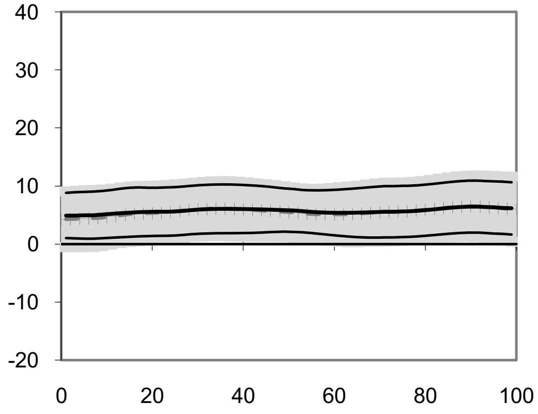

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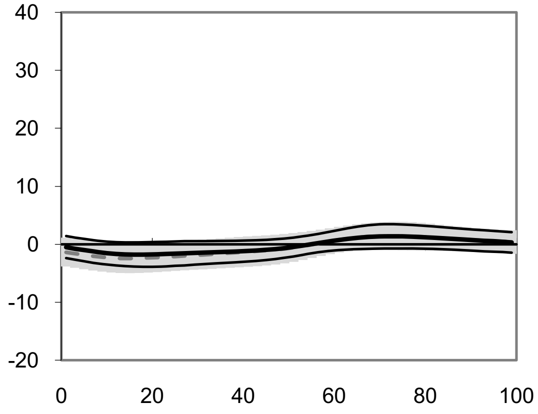
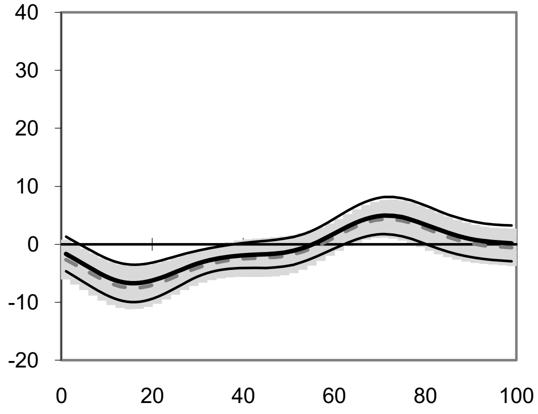
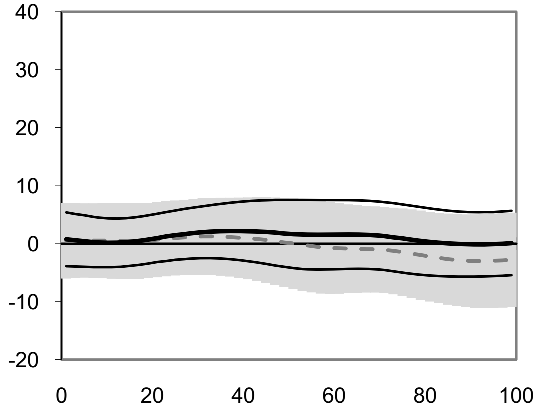


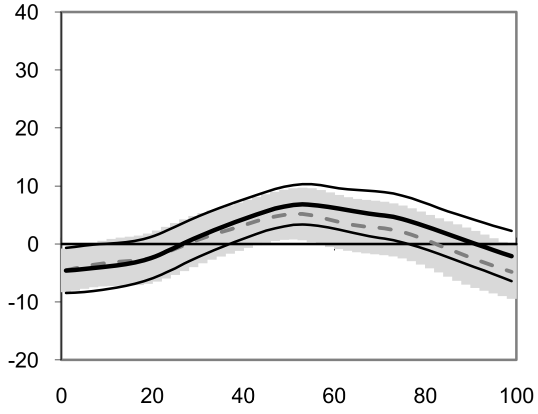
Thorax Side flexion (wrt Pel)

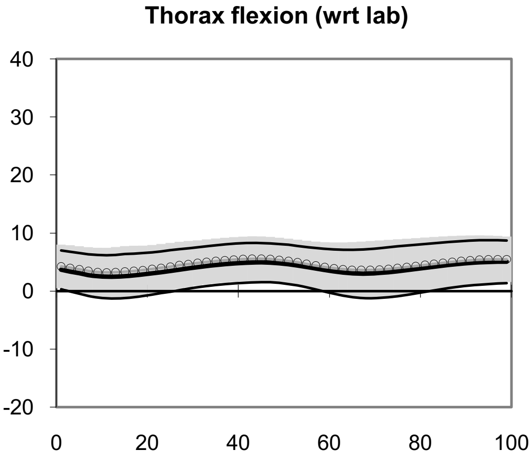


Thorax Rot (wrt Lab)

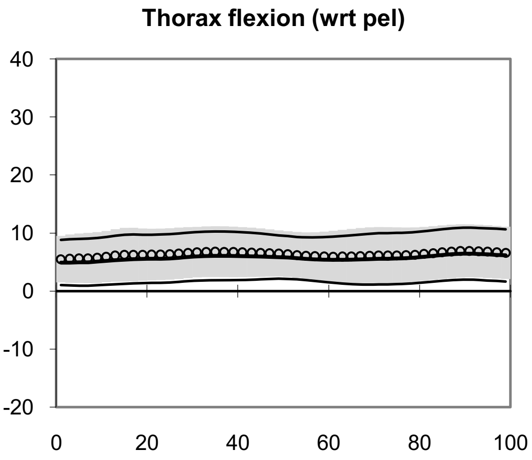


Thorax Rot (wrt Pel)

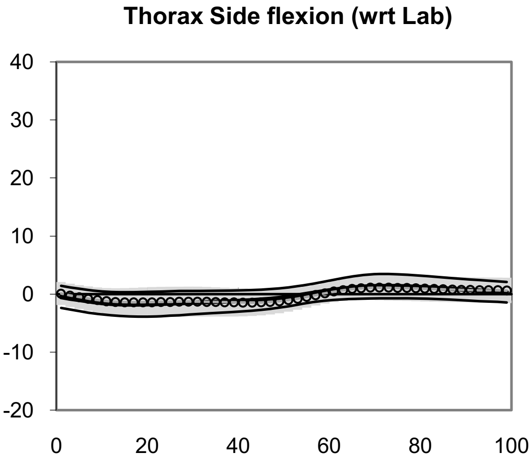




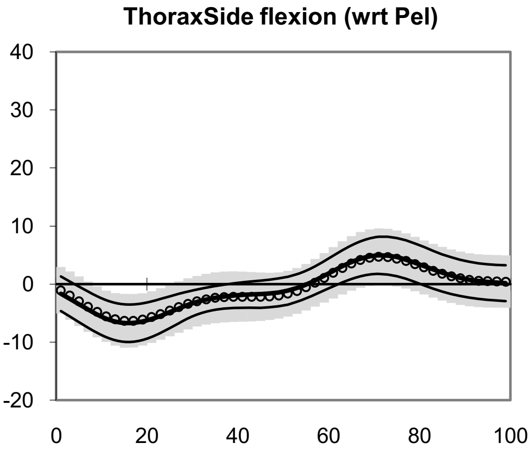
Thorax flexion (wrt lab)



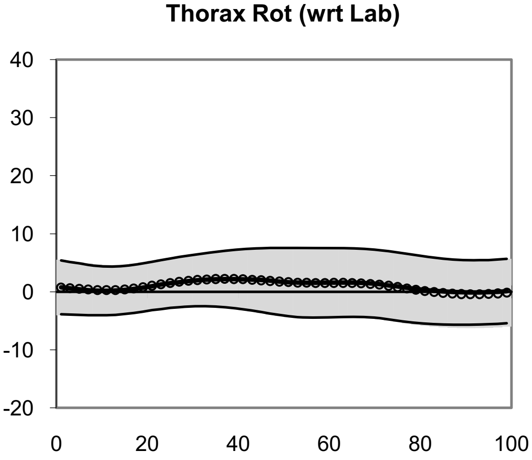
Thorax flexion (wrt pel)



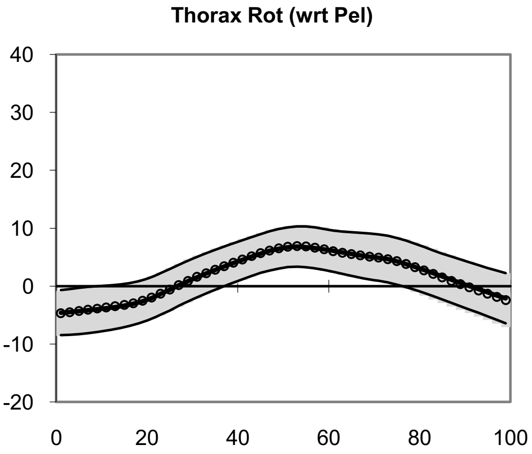
Thorax Side flexion (wrt Lab)



ThoraxSide flexion (wrt Pel)



Thorax Rot (wrt Lab)



Thorax Rot (wrt Pel)

None of the authors had any financial or personal conflict of interest with regard to this study.