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Optimal markers' placement on the thorax for clinical gait analysis

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ABSTRACT

Although, several thorax models have been proposed for clinical gait analysis, none has received widespread acceptance nor been subject to any extensive validation work, especially for the marker set to use. The aim of this study was thus to determine the optimal and minimal makers' placement on the thorax for clinical gait analysis.

Ten healthy subjects have performed a series of movements (arm, head, trunk) with large amplitude during walking. Reflective markers were taped on the thorax (C7, T2, T4, T6, T8, T10, T12, sternum, clavicles and ribs) and their 3D positions were captured with an opto-electronic system. Each combination of 3 markers has been tested. The global error of each model was computed with the estimated position of the markers considering the thorax segment as a solid segment.

Two families of marker sets were identified with the lowest error. The first family was composed by two anterior and one posterior marker on the thorax (incisura jugularis (IJ), xiphoid process, and T8). The second family was composed by two posterior and one anterior maker (IJ, T2 and T8 or T10). Even, if these two families of marker sets presented a similar error for marker position, the angles obtained from these marker sets showed large differences especially for the axial rotation movement of the trunk (up to 40.1°).

The optimal and minimal maker set identified with a variety of large movements of the trunk, head and arms was IJ, T2 and T8 or T10.

1. Introduction

During gait, the upper-body is considered as the 'passenger' unit whereas the lower-body is the locomotor unit [1]. The trunk is the heaviest segment of the body and has the largest contribution to forward momentum [2]. Numerous compensatory mechanics appear at the trunk level while walking in people with a variety of conditions [3]. In order to fully understand pathologic gait, trunk kinematics should thus be considered an important component of gait analysis [4,5].

There is a lack of consensus as to how to quantify the movements of the trunk in clinical gait analysis. The trunk as a whole is not rigid and can be divided into the lumbar and thorax segments. At present, a variety of models of the thorax based on different marker placements exist. Davis et al. [6] placed the markers about mid-way along the left and right clavicles and over the C7 vertebra. Bartonek et al. [7] proposed a similar approach based on basic trigonometry using four markers on the acromium processes, the ASIS and a marker on a 5 cm wand placed over the L5 vertebra. No axis systems were defined. Starr et al. [8] proposed using what Davis and Ounpuu referred to as the shoulder axis system as an indicator of thorax movement. Nguyen and Baker [9] and Gutierrez et al. [10] both used a model based on markers placed or estimated on the mid-line of the thorax. Both models used the markers C7, manubrium sternal or mid-point between clavicles, sternum (and T10 for Gutierrez et al.) to define the axis system. The model of Gutierrez et al. [10] was that implemented in the Vicon Full Body PlugInGait (Vicon Motion Systems, UK) and has been used in several studies [4,11]. The International Society of Biomechanics recommends the use of markers over the incisura jugularis (IJ) on manubrium sternal, the processus xyphoid (PX), C7 and T8 [12]. The ISB and Gutierrez et al. model are quite similar (ISB used T8 whereas Gutierrez et al. used T10). The team of Lamoth [13] used a cluster of three markers attached to the thorax. Recently, Leardini et al. [14] proposed a new model considering the thorax and the shoulder girdle separately. They proposed to use a marker set defined by PX, PJ, T2 and the midpoint between the inferior angles of most caudal points of the two scapulae (MAI).

None of these models has been rigorously validated model and this is becoming an increasingly important focus for research

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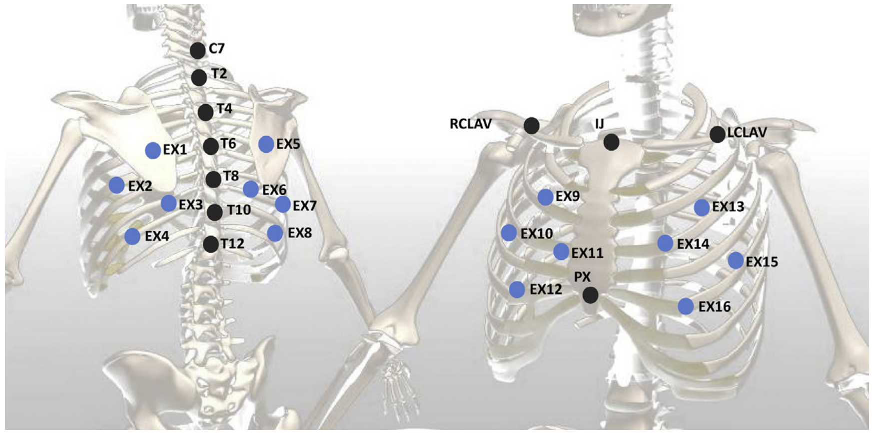

Fig. 1. Marker placement on the thorax.

[4,9,10,15,16]. Leardini et al. [17] have compared 8 current used models for clinical gait analysis. They found a high discrepancy between models.

The aim of this study was thus to define a model of an individual thorax segment. Two steps are essential. The first is to identify a set of three or more markers that defines a technical coordinate system. The principal concern here is that these are the markers that move least with respect to the underlying bony segment. The second is to define an anatomical coordinate system that is fixed in relation to the technical coordinate system but has axes that can be assumed to have some clinical meaning. The first step has not been investigated for the thorax and this was the primary aim of this paper.

2. Methods

2.1. Participants

The study was approved by the local ethics committee. All participants received written and oral information and signed an informed consent statement.

Ten volunteers, five males and five females, were enrolled in the study (mean age: 30.1 ± 4.3 year; height: 170.4 ± 6.6 m, weight: 63.9 ± 9.0 kg). To be included in this study, each participant had to be able to move head, arms, shoulders and trunk in all the direction and large amplitude without any pain. The exclusion criteria were previous back pain, past spine or shoulder surgery, balance or vestibular problems.

2.2. Markers and model sets

Eleven 16 mm markers were placed on bony landmarks of the thorax (black markers in Fig. 1) identified according to van Sint Jan [18]. Each possible configuration of 3 markers (or 4 markers in the case of using clavicles or shoulders) fulfilling the following scientific and anatomical conditions were tested: (1) markers placed on thorax or clavicles, (2) a minimum distance of 4 vertebrae between spine markers, (3) two markers on the spine or on the sternum to define the proximal (Y) axis, (4) one marker on the spine or on the sternum to define anterior (X) axis or one marker on each clavicle to define the mediolateral (Z) axis. Additionally, 16 extra markers (grey markers EX. in Fig. 1) were placed around the thorax to better render the kinematics of the mass of this segment.

The anatomical co-ordinate systems derived from the technical marker set were defined as follows: The origin of the thorax coordinate system was defined by the upper spine marker. The Y axis is defined by two markers, either on the spine or on the sternum and pointing upward. The X axis was defined to be anterior and perpendicular to the Y axis through, either one anterior (sternum) or posterior (spine) marker. The Z axis is defined by mutual perpendicular (cross-product) between Y and X axis. Thorax angles (tilt, obliquity and rotation) were defined according ISB recommendations [12]. During a 3 s static trial the reference shape of each marker set and their corresponding anatomical co-ordinate system was determined for all segments and stored for future use by a custom-made Matlab (MathWorks, Natick, MA, USA) package [19]. Reference shape of an idealized marker set made of all 16 markers was also stored.

2.3. Motion tasks

After a 5 min warm-up, all participants underwent familiarization in the experimental procedures. As most of persons with gait deviations have larger trunk, head and arm movements than asymptomatic persons [4,5,10,20,21], each participant was asked to perform twice a set of movements during walking at self-selected speed: (1) no specific movement, (2) arm movements, (3) head movements, (4) flexion/extension of the trunk, (5) lateral bending the trunk, (6) axial rotation of the trunk and (7) movements of the trunk in all directions. The participants were instructed to perform the movement with the maximum of amplitude.

2.4. Data collection

An opto-electronic system (VICON MX3+, Vicon Motion Systems, Oxford, UK) with seven cameras operating at 100 Hz was used to capture the three-dimensional position of the markers for each movement of each subject. Two force plates (AccuGait, AMTI, Watertown, MA) or manual detection with the trajectory of heel and toe markers were used to identify gait cycle events. Nexus software (Vicon Motion Systems, Oxford, UK) was used to capture, reconstruct, label, interpolate (maximum of 5 points) and to smooth trajectories using the Woltring splines filter (mse = 10). The first complete gait cycle by movement and by subject with gaps inferior to 5 frames in the marker trajectories has been used for the data analysis.

2.5. Data analysis

Consequently, 52 marker sets were tested for each movement of each person. For each of the 52 marker sets the method described in Soderkvist and Wedin [22] was used to determine the best rigid body transformation in the least square sense between each marker set reference shape and the actual position of the markers of the marker set. This operation was repeated for all frames and all movement trials. The transformation matrix thus obtained was applied to the idealized marker set reference shape to create virtual markers (P_l). The residual between the virtual markers (P_l) and the actual markers ($\bar{P}_l$) was calculated for all the frames. The RMS differences between P_l and $\bar{P}_l$ reflects both soft tissue artefacts and thorax deformation effects between the markers of a given marker set and all the markers of the thorax. The Root Mean Square Error (RMSE) for a marker set i was therefore calculated for each subject s and each condition c:

$$RMSE_{isc} = \sqrt{\frac{\sum_{k=1}^{m}\sum_{l=1}^{f}(P_l-\bar{P}_l)^2}{m\times f}} \quad (1)$$

where respectively m and f are the number of markers and frames. The mean of the RMSE by patient and condition were the global error of a market set i:

$$GlobalError_i = \frac{1}{n\times d}\sum_{s=1}^{n}\sum_{c=1}^{d} RMSE_{isc} \quad (2)$$

where n and d are the number of subject and condition. It was assumed that technical marker sets showing the lowest values of global error were those which are best representing the kinematics of the overall thorax segment.

The global error for a specific marker $MarkerError_m$ was computed as the mean of the $RMSE_{isc}$ of all the marker sets containing this specific marker.

Table 1
Mean, maximal and minimal error ($RMSE_{isc}$) for the 52 marker sets. The $SCORE_i$ were reported in percentage. The $SCORE_i$ greater than 80% were highlighted in grey.

Marker sets	Female and male ($n=10$)				Female ($n=5$)				Male ($n=5$)			
	%	Mean	Max	Min	%	Mean	Max	Min	%	Mean	Max	Min
PX_IJ_T8	95.5	9.2	17.1	4.2	90.9	8.4	16.9	4.2	100.0	10.0	17.1	4.2
PX_IJ_T6	92.4	9.3	17.3	4.2	87.9	8.4	16.5	4.2	97.0	10.1	17.3	4.2
T2_T10_IJ	83.3	9.8	21.8	4.3	81.8	8.7	16.3	4.3	84.8	10.8	21.8	4.4
T2_T8_IJ	83.3	9.7	21.2	4.0	84.8	8.7	15.7	4.4	81.8	10.6	21.2	4.0
C7_T8_IJ	80.3	9.6	18.6	4.2	78.8	8.6	14.6	4.2	81.8	10.6	18.6	4.5
PX_IJ_T10	80.3	9.9	20.9	4.3	69.7	9.0	17.1	4.3	90.9	10.8	20.9	4.7
PX_IJ_T4	78.8	9.8	21.7	4.5	81.8	8.5	16.3	4.5	75.8	11.1	21.7	4.6
T2_T10_CLAV	78.8	9.9	21.1	4.1	87.9	8.6	16.8	4.3	69.7	11.3	21.1	4.1
C7_T10_CLAV	77.3	9.9	21.7	4.2	87.9	8.6	16.9	4.5	66.7	11.3	21.7	4.2
C7_T10_IJ	75.8	9.8	20.3	4.2	72.7	8.8	15.3	4.2	78.8	10.8	20.3	4.7
T2_T6_IJ	75.8	9.8	19.9	4.2	75.8	9.0	18.1	4.4	75.8	10.6	19.9	4.2
T4_T10_CLAV	72.7	10.0	20.7	4.2	81.8	8.6	16.5	4.7	63.6	11.3	20.7	4.2
T6_T10_CLAV	69.7	10.1	20.0	4.1	81.8	8.7	16.3	4.6	57.6	11.4	20.0	4.1
C7_T6_IJ	65.2	9.8	17.5	4.2	69.7	8.7	16.2	4.2	60.6	10.8	17.5	4.5
T2_T8_CLAV	63.6	10.0	20.4	4.2	75.8	8.6	15.0	4.3	51.5	11.5	20.4	4.2
T4_T10_IJ	63.6	10.4	23.5	4.6	66.7	9.4	18.1	4.6	60.6	11.5	23.5	4.6
T4_T8_CLAV	63.6	10.2	21.6	4.2	78.8	8.7	15.1	4.3	48.5	11.7	21.6	4.2
C7_T8_CLAV	59.1	10.0	19.6	4.2	66.7	8.5	14.7	4.3	51.5	11.5	19.6	4.2
T6_T12_CLAV	57.6	10.3	22.9	4.2	51.5	9.2	15.8	4.6	63.6	11.4	22.9	4.2
T8_T12_CLAV	56.1	10.4	22.4	4.1	51.5	9.3	15.7	4.8	60.6	11.5	22.4	4.1
C7_T4_IJ	54.5	10.4	18.6	4.4	54.5	8.9	18.4	4.4	54.5	11.8	18.6	4.5
T2_T12_IJ	54.5	10.5	23.5	4.5	42.4	9.7	19.7	4.5	66.7	11.3	23.5	4.9
T2_T10_PX	53.0	10.2	23.4	4.8	57.6	9.0	17.5	4.8	48.5	11.3	23.4	4.8
T4_T12_CLAV	53.0	10.4	23.5	4.3	45.5	9.2	16.2	4.5	60.6	11.5	23.5	4.3
C7_T8_PX	51.5	10.2	21.3	4.6	48.5	9.1	14.8	4.6	54.5	11.3	21.3	4.7
T4_T8_IJ	51.5	10.5	23.2	4.1	45.5	9.6	17.4	4.8	57.6	11.4	23.2	4.1
C7_T10_PX	45.5	10.2	22.9	4.8	45.5	9.1	16.9	5.0	45.5	11.4	22.9	4.8
T2_T8_PX	45.5	10.3	21.5	4.5	39.4	9.3	16.1	4.6	51.5	11.2	21.5	4.5
T4_T12_IJ	45.5	10.9	25.1	4.8	36.4	10.2	21.0	4.8	54.5	11.7	25.1	4.9
C7_T12_CLAV	43.9	10.6	24.1	4.3	48.5	9.4	16.7	4.5	39.4	11.7	24.1	4.3
T6_T10_IJ	42.4	11.3	26.0	4.7	42.4	10.3	20.2	4.7	42.4	12.3	26.0	4.9
T2_T12_CLAV	40.9	10.4	23.6	4.3	39.4	9.3	16.5	4.5	42.4	11.6	23.6	4.3
C7_T6_PX	39.4	10.6	20.2	4.7	36.4	9.5	17.1	4.7	42.4	11.8	20.2	5.2
T2_T6_PX	39.4	10.6	20.1	4.7	30.3	9.8	20.1	4.7	48.5	11.5	19.8	5.5
C7_T6_CLAV	37.9	10.7	20.7	4.5	39.4	9.1	16.7	4.5	36.4	12.3	20.7	4.9
PX_IJ_T2	36.4	10.9	28.4	4.7	45.5	9.3	17.5	4.8	27.3	12.5	28.4	4.7
T2_T6_CLAV	36.4	10.8	24.0	4.5	42.4	9.2	17.0	4.5	30.3	12.4	24.0	5.1
T2_T12_PX	34.8	10.7	24.3	4.7	33.3	9.7	17.4	4.7	36.4	11.8	24.3	4.9
C7_T12_IJ	33.3	10.8	23.3	4.4	24.2	10.0	19.5	4.4	42.4	11.6	23.3	5.1
T4_T10_PX	30.3	10.8	25.9	5.1	36.4	9.6	17.5	5.1	24.2	12.0	25.9	5.2
C7_T12_PX	28.8	11.0	24.1	4.6	24.2	9.9	17.1	4.6	33.3	12.1	24.1	4.8
C7_T4_PX	28.8	11.6	22.4	4.3	33.3	10.1	15.8	4.3	24.2	13.0	22.4	6.3
PX_IJ_CLAV	28.8	11.2	23.8	4.7	33.3	9.7	17.8	4.7	24.2	12.7	23.8	5.3
C7_T4_CLAV	25.8	11.8	26.3	4.3	39.4	9.8	17.6	4.3	12.1	13.8	26.3	6.2
T4_T12_PX	25.8	11.1	25.9	4.8	24.2	10.1	18.1	4.8	27.3	12.1	25.9	5.2
T6_T12_IJ	24.2	11.7	26.9	4.8	15.2	11.1	22.6	4.8	33.3	12.3	26.9	5.1
T4_T8_PX	21.2	11.1	24.4	4.7	9.1	10.0	17.2	5.0	33.3	12.1	24.4	4.7
PX_IJ_T12	18.2	11.9	28.3	4.7	9.1	10.9	23.8	4.7	27.3	12.8	28.3	5.2
T6_T10_PX	13.6	11.5	27.4	5.1	15.2	10.3	20.4	5.1	12.1	12.6	27.4	5.5
T8_T12_IJ	13.6	12.6	28.9	5.0	12.1	12.1	24.6	5.0	15.2	13.2	28.9	5.4
PX_IJ_C7	12.1	12.8	44.0	5.1	15.2	10.8	22.7	5.1	9.1	14.8	44.0	5.4
T6_T12_PX	12.1	11.7	26.9	5.0	9.1	10.7	18.8	5.0	15.2	12.6	26.9	5.5
T8_T12_PX	4.5	12.4	27.7	5.1	3.0	11.6	20.0	5.1	6.1	13.3	27.7	5.5

2.6. Identification of best marker sets

For each subject and each condition a score ($SCORE_{isc}$) of 0 or 1 was given for each marker set i according to the following rule:

$$SCORE_{isc} = \begin{cases} 1 & \text{if } RMSE_{isc} < Median(RMSE_{sc}) \\ 0 & \text{if } RMSE_{isc} > Median(RMSE_{sc}) \end{cases} \quad (3)$$

where $Median(RMSE_{sc})$ is the median of the $RMSE_{isc}$ for all marker sets for a given condition and subject.

The overall score for a given marker set was then computed as:

$$SCORE_i = \frac{100}{n \times d} \sum_{s=1}^{n} \sum_{c=1}^{d} SCORE_{isc} \quad (4)$$

$SCORE_i$ therefore represents the percentage where a given marker set was in the best subset of marker sets for all subjects and conditions. Marker sets obtaining a $SCORE_i$ above or equal to 80% were selected for further analysis.

In order to assess how much the choice of a given marker set affected the kinematics results, the range of movement in the sagittal, frontal and transverse planes were compared for the selected marker sets.

3. Results

Due to marker occlusion, axial rotation, flexion/extension, all direction of the trunk were not analyzed in one subject and lateral bending of the trunk was not analyzed in two subjects.

The global mean, maximum and minimal error of each marker set is presented in Table 1. On 52 marker sets, 6 obtained a *SCORE* above 80%, meaning they were almost always part of the best subset of marker sets. These marker sets were the PX_IJ_T8, PX_IJ_T6, T2_T10_IJ, T2_T8_IJ, and PX_IJ_T10. For the male cohort only, the same 6 marker sets obtained a score above 80%. For the female cohort only, in addition of the first four marker sets mentioned above, PX_IJ_T4, T2_T10_CLAV, C7_T10_CLAV, T4_T10_CLAV and T6_T10_CLAV were scored above 80%.

On the total group, the average error $RMSE_i$ for each marker sets was 9.2 mm for the best one and 12.8 mm for the worst one. Maximal error for all conditions and subjects was 17.1 mm for the best marker set and 44.0 mm for the worst one.

Fig. 2 presents the global error of each marker ($MarkerError_m$) for each gait condition. In normal gait, the error was 6.6 mm and there were small variations between all the considered markers. For arm movements during gait, the mean error was from 11.7 mm, marker set using the markers CLAV showed the largest error with 12.4 mm. C7 was the most affected markers for head movements during walking with 8.8 mm. The mean error for all the markers was 8.0 mm. For all the trunk movements (Flexion/Extension; Lateral leaning, Axial Rotation and All direction) during gait, the worst marker was T12 with respectively 10.3, 10.3, 16.5 and 14.8 mm.

Fig. 3 shows the thorax kinematics range for one gait cycle computed with the best marker sets during specific movements. In the sagittal plane, the marker set influenced the position but had a moderate effect on amplitude (Fig. 4). The maximum difference observed between the 6 best marker sets was 8.9° for the flexion/extension of the trunk. In the frontal plane, there were important differences between marker sets (maximum difference: 31.3° for axial trunk rotation). Two marker set families emerged. The first family was composed by the PX and IJ markers whereas the second family was composed by the IJ and dorsal markers (C7 or T2 and T8 or T10). In the transverse plane, the maximal difference appeared also for the axial trunk rotation (40.1°). For this movement, the second family of markers had higher amplitude than the first one; that was the opposite for the frontal plane.

4. Discussion

The aim of this study was to determine the optimal and minimal markers' placement on the thorax for clinical gait analysis. We have identified 6 thorax marker sets that presented the best SCORE during large trunk, arms and head movements. In these 6 marker sets, two families can be highlighted. The first family (Anterior Thorax) is composed by PX, IJ and one low back thorax markers (T6, T8 or T10). The second family (Posterior Thorax) is composed by IJ, one high back thorax markers (C7 or T2) and one low back thorax markers (T8 or T10). Even, if these two families presented a similar SCORE, the angles showed large differences especially for the axial rotation movement of the trunk. Leardini et al. [17] have compared 8 trunk models for clinical gait analysis and found similar results with a maximal difference amplitude of 52.6° for frontal plane assessment during an axial rotation movement. Surprisingly, the

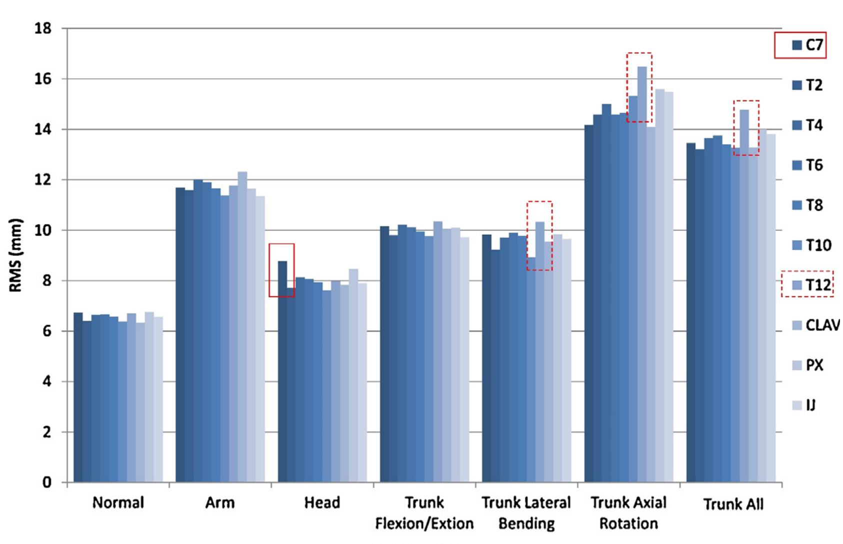

Fig. 2. Global error for each marker for each gait condition. The rectangle highlight particular results for C7 during head movement and the dashed rectangles highlights particular results for T12 for Lateral bending, Axial rotation and All movement of the trunk.

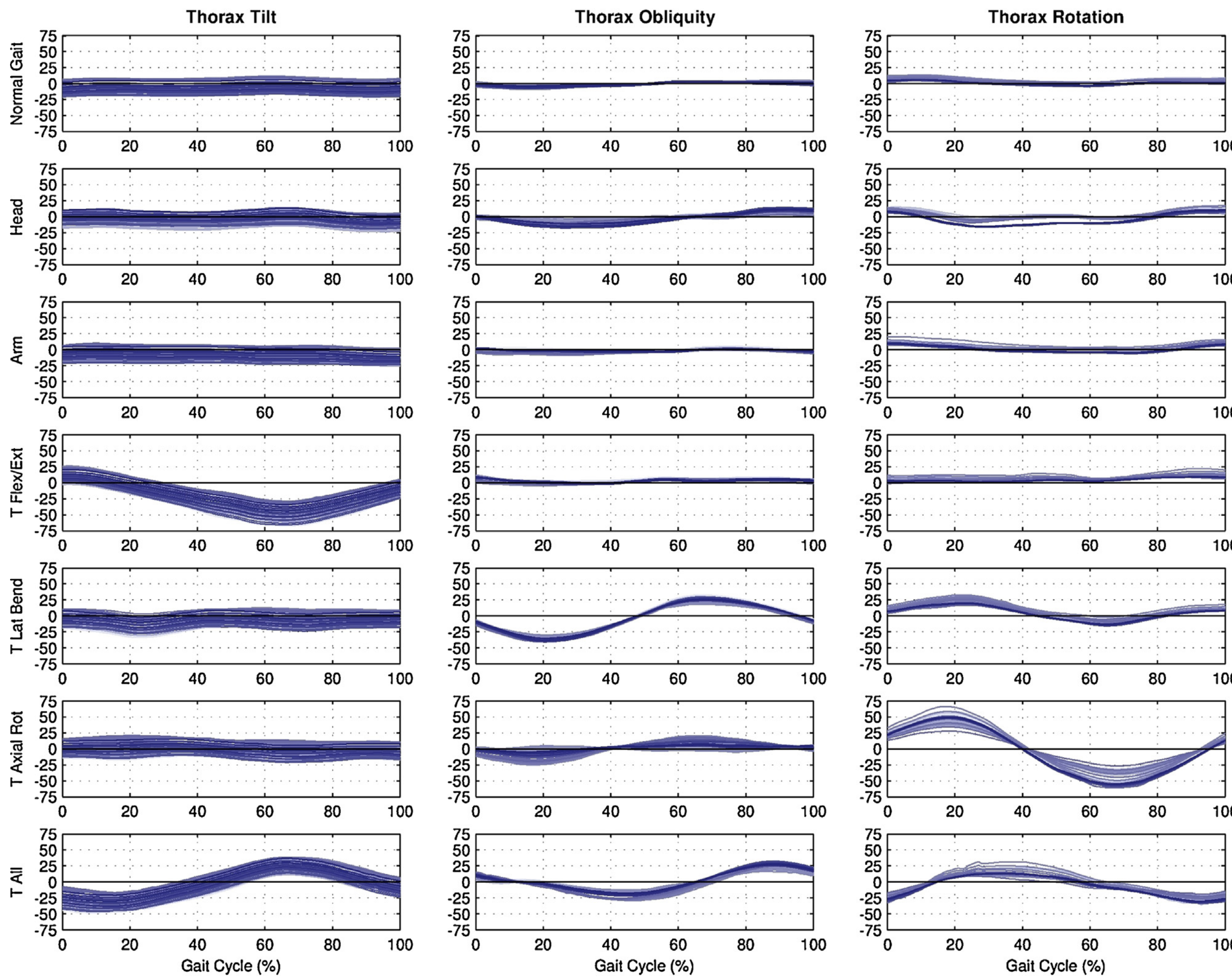

Fig. 3. Thorax kinematic for each gait condition for a typical subject T-trunk.

"Anterior Thorax" family showed higher movement amplitude in the frontal plane during axial trunk rotation than during lateral bending; it should be the inverse. So, even if the error of the markers was low for these marker sets, they seem not adequate to measure the frontal plane according the obtained range of motion. The "Posterior Thorax" family showed a better coherence between the range of movement and the movements performed. Moreover, it can be practically difficult and/or embarrassing to place precisely the PX marker in women.

For the higher thorax part, C7 appeared to be influenced a lot by head movements. Consequently C7 should be not used to quantify the thorax during clinical gait analysis. T2 should be preferred. For the lower thorax, marker sets using T12 showed highest error during axial rotation or all direction of the trunk. Therefore a higher thorax vertebrae should be used (e.g. T10 or T8). In our results T8 and T10 models showed similar results. Recently, Leardini et al. [14] proposed to use the midpoint between the inferior angles of most caudal points of the two scapulae (MAI) because the identification of this point is simple and repeatable. Haneline et al. [23] reported that this landmark usually corresponds to the level of T9. Even, if we had not tested specifically this marker position, its localization around T10-T8 (best low back thorax markers) and simplicity of identification should be of interest to be included in potential markers to define a good marker set for the assessment of the thorax kinematics in clinical gait analysis. Bearing in mind the independence of shoulders with the thorax segment and our results, the acromion or clavicule markers should not be used to quantify the thorax in clinical gait analysis

Considering the previous discussion, the optimal and minimal marker set for the thorax in clinical gait analysis should contain IJ, T2 and T10 or T8. MAI could be an interesting candidate for the T10-T8 location but need to be tested, especially the reliability of the position in spine with deviations. All these landmarks (IJ, T2, T10 or T8) are simple to localize which is an important criterion in the choice of the marker set in order to be reliable and minimize errors.

At minimal, three markers are needed to create a model but it's possible to define a segment with more markers to increase the tracking accuracy of the segment [24]. For example, a fourth marker could be added at mid-distance of sternum for women or at the PX for men. This marker may not be used to create the model of the thorax but to increase the tracking of the segment or to replace an eventual hidden model marker on several frames. In this study, we tested the optimal marker set with the minimal numbers of markers (3 or 4 in special cases). It might be that marker sets with more markers give better results but this is an issue beyond the scope of this analysis.

This study has several limitations. The main limitation is certainly that the thorax was considered as one rigid segment although it is composed by several segments (e.g. vertebrae, ribs, etc.) and joints between these segments. More complete marker sets and models for the thorax [25,26] were developed but do not seem suitable for clinical gait analysis. They are more used to

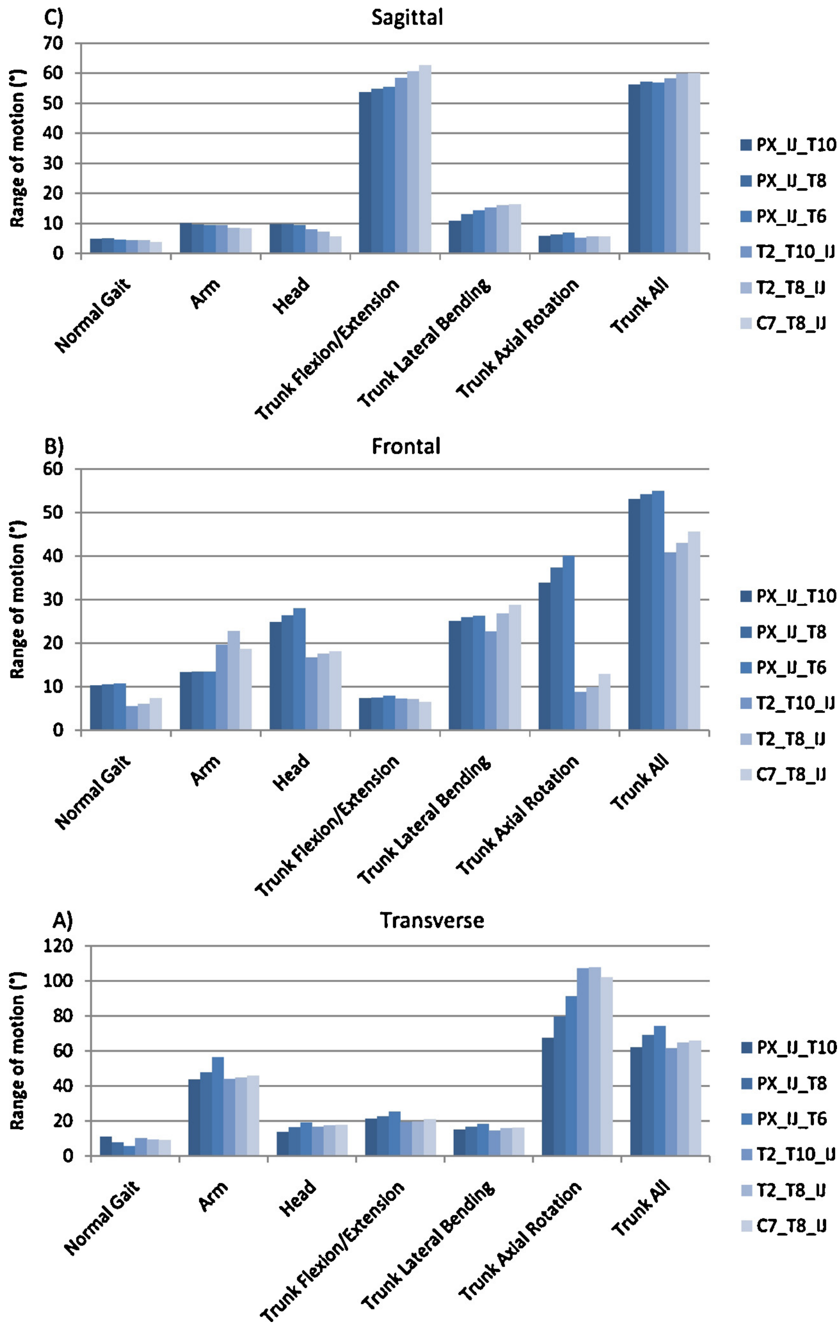

Fig. 4. Range of motion of the thorax kinematics obtained with the 6 best marker sets. (A) Sagittal plane, (B) frontal plane, and (C) transverse plane.

assess spine mobility or deformations, A second limitation concerns the position of the markers. The position was identified by an experimented person with the respect of location and palpation recommendations [18]. However, error of localization is always possible. Finally, the third limitation is that this study was performed on asymptomatic participants with artificial movements of the trunk. We expected that large movements of trunk, head and arms gave a good spectrum of maximal possible compensations or alterations existing in patients such as cerebral palsy [4], amputees [5], Parkinson [21] or myelomeningocele [10].

In conclusion, this study provides an extensive investigation of possible marker sets on the thorax for clinical gait analysis. The optimal and minimal marker set identified with a variety of large movements of the trunk, head and arms was IJ, T2 and T8 or T10. Further studies are necessary to test the accuracy, the reliability and the clinical pertinence of this optimal and minimal marker set on the thorax.

Conflict of interest statement

The authors certify that there is no conflict of interest with any financial and personal relationships with other people or organizations that could inappropriately influence this work.

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