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Quantitative evaluation of linked rigid-body representations of the trunk

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ABSTRACT

Background: The trunk is often simplified as a small number of rigid-body segments to reduce the complexity of its multi-segmental structure. However, such rigid-body representations of the trunk may overlook its flexible movement owing to its multi-segmental structure.

Research question: The purpose of this study is to quantitatively assess the effects of the deformability on the resultant trunk kinematics when the trunk is modeled with numerous rigid-body segments.

Methods: Three-dimensional kinematic data of 10 male subjects were obtained during static and dynamic trials. The trunk in both static and dynamic trials was modeled as a single rigid-body segment or as two, three, or six linked rigid-body segments, and a non-linear optimization analysis was performed to minimize the difference between the actual and modeled position data. Position errors were evaluated to assess the difference in three-dimensional positions between the actual and modeled data for each model. The total angular displacement was evaluated to examine to what extent each model describes the actual multi-segmental trunk movement.

Results: The position error between the modeled and actual kinematic data of the trunk was up to 12 mm and 11 mm when the trunk was simplified as one segment, but the error decreased to 5 mm and 7 mm when the trunk was modeled with six segments during the static and dynamic trials, respectively. The total angular displacement increased as the number of rigid-body segments increased during both trials.

Significance: These results imply that a small number of linked rigid-body representations underestimates the actual multi-segmental trunk movement during dynamic movement. These findings are useful in determining the optimal number of rigid-body segments for analysis of the trunk.

1. Introduction

In three-dimensional motion analyses, the trunk is often simplified as a single rigid-body segment or as a small number of linked rigid-body segments to reduce the complexity of its multi-segmental structure [1,2]. However, such rigid-body representations of the trunk can overlook its flexible movement as the trunk deforms during dynamic movements owing to its multi-segmental structure composed of cervical, thoracic, and lumbar vertebrae [3]. Therefore, the optimal linked rigid-body representation of the trunk should be determined depending on the study aims and required accuracy for the analysis to sufficiently describe complex trunk movement.

When analyzing the kinematics of the trunk during dynamic movements, the number of rigid-body segments to model the trunk significantly affects the resultant trunk kinematics [4,5]. Different linked rigid-body representations of the trunk, which adopt several numbers of rigid-body segments, result in different patterns of angular displacement for each segment and range of motion during dynamic movement [4–19]. It is valuable to quantitatively assess how well linked rigid-body representations with different numbers of segments can describe actual trunk movements. This will help to determine the optimal number of rigid-body segments for the analysis of trunk dynamics.

Several previous studies have quantitatively assessed the resultant differences in trunk kinematics between models with different numbers of rigid-body segments [6,7]. Although these studies described trunk kinematics based on spine movements, the trunk flexibly deforms due to its multi-segmental structure and surrounding tissues, which could not be entirely described with spine kinematics only, as the authors have recently reported [3]. Such deformability of the trunk should also be considered to determine the optimal number of rigid body representation which sufficiently describes trunk kinematics.

Therefore, the purpose of this study was to quantitatively assess the effects of the trunk deformability on the resultant trunk kinematics, when the trunk is modeled with a different number of rigid-body segments. The trunk was modeled with one, two, three, or six linked rigid-body representations. The differences in the three-dimensional kinematics between the actual and modeled data were assessed in static and dynamic movement conditions.

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2. Methods

2.1. Subjects

Ten male subjects participated in this study (mean age: 22.6 ± 1.5 years, mean height: 1.70 ± 0.05 m, mean body mass: 64.6 ± 6.0 kg). All participants reviewed and signed an informed consent form, and the study was approved by the Institutional Review Board at Ritsumeikan University Biwako-Kusatsu Campus, Japan.

2.2. Measurement protocol

Three-dimensional kinematics under static and dynamic movement conditions were examined in this study. For the static trials, the subjects were asked to move the trunk to their limit of motion in each plane of motion (i.e., trunk lateral bending to the left and right sides, axial rotation to the left and right sides, thorax flexion, and thorax extension) and to hold that posture for 5 s. This protocol was performed to assess how well the linked rigid-body representations describe the actual posture of the trunk at maximum range of motion. For the dynamic trial, the subjects were asked to walk barefoot along a 5-m walkway at a self-selected speed. This protocol was adopted to assess to what extent the linked rigid-body representations describe the actual multi-segmental trunk movement during dynamic movement.

2.3. Data collection

A 24-camera motion capture system (MAC3D, Motion Analysis Corporation, California, USA) captured the entire body motion. Three-dimensional position data were obtained at 250 Hz and were then low-pass filtered at 8 Hz using a fourth-order digital Butterworth filter. The motion capture system offered submillimeter accuracy, and its residual systematic error was less than 0.5 mm at the time of calibration. Seventy reflective markers were placed on the back (Fig. 1a) and front (Fig. 1b) sides of the trunk at regular intervals to define 48 triangular areas on each side. The markers were placed at the level of the seventh cervical vertebra (C7), third thoracic vertebra (T3), sixth thoracic vertebra (T6), ninth thoracic vertebra (T9), twelfth thoracic vertebra (T12), third lumber vertebra (L3), and first sacral vertebra (S1). The markers placed on the back and front sides of the trunk were defined as B- and F-markers, respectively. The trunk was divided into seven rows (from B- or F-Row 1 to B- or F-Row 7) and five columns (from B- or F-Column 1 to B- or F-Column 5). Additional markers were placed at the posterior superior iliac spine and anterior superior iliac spine to define the pelvic reference frame [5].

2.4. Data analysis

The trunk was modeled with one (M1), two (M2), three (M3), or six (M6) linked rigid-body segments to quantitatively assess how well the linked rigid-body representations of the trunk describe the actual complex trunk movements (Fig. 2). The trunk was divided by the number of segments in each model, and the endpoints of each segment were determined by the bony landmarks on the spine (M1: C7-S1; M2: C7-T9, and T9-S1; M3: C7-T6, T6-T12, and T12-S1; M6: C7-T3, T3-T6, T6-T9, T9-T12, and T12-S1). A local reference frame was defined for each rigid-body segment. The origin of the local coordinate system was set at the averaged position of the markers placed on the lower base of each segment (Fig. 2). The vertical axis (z-axis) was defined from the origin to the averaged position of the markers placed on the upper base of each segment. The anterior-posterior axis (x-axis) was defined as the line perpendicular to the plane defined by the z-axis and the line connecting the origin and the averaged position of the Column 1 markers placed on the front and back sides, pointing in the anterior direction. The medial-lateral axis (y-axis) was defined as the line perpendicular to both the z- and x-axes, pointing to the left. Two adjacent segments of the trunk were linked with a ball joint, and thereby M1, M2, M3, and M6 individually had six, nine, twelve, and twenty-one degrees of freedom, respectively. The position data were determined with respect to the local coordinate system defined on each rigid-body segment.

The position error, the difference in the three-dimensional position between the actual and modeled data, was calculated to quantify how accurately these models describe the actual trunk kinematics. A simultaneous transformation matrix (STM) from the local to global coordinate system was determined for each rigid-body segment. The rotation matrix of the STM was determined by a $Y - X' - Z''$ Euler-angle sequence. The distance between the actual and modeled data was then calculated to quantify the position error in each movement condition. The perpendicular distance from the center of the triangular area defined by the actual data to the triangular plane defined by the modeled data was calculated. A set of parameters for the STM to minimize the averaged perpendicular distance for all pairs of the actual and modeled data was then found with a nonlinear optimization analysis (fmincon in the MATLAB optimization toolbox; Fig. 3). The minimized distance was used as the position error for each model to assess how well each linked rigid-body representation described the actual trunk position.

The total angular displacement for each model was calculated to determine to what extent each model describes the actual multi-segmental trunk movement. Joint angles between two adjacent segments were calculated based on the parameters for the STM derived using the nonlinear optimization analysis. The angles about the Y, X′, and Z″ axes were obtained as angles of lateral bending (LB_x′), axial rotation (AR_z″), thorax flexion (TE_y), and thorax extension (TF_y) between

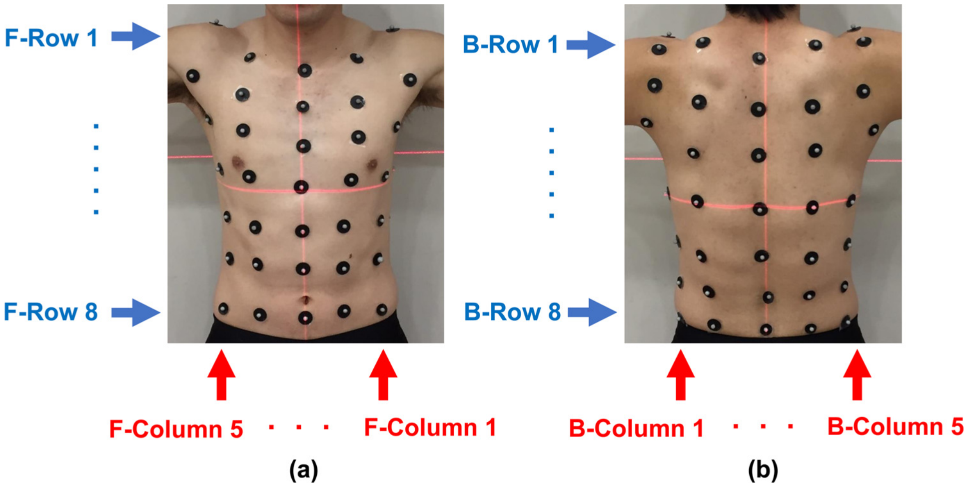

Fig. 1. Placement of the markers. Seventy reflective markers were placed on the back (a) and front (b) sides of the trunk on the level of the seventh cervical vertebra (C7), third thoracic vertebra (T3), sixth thoracic vertebra (T6), ninth thoracic vertebra (T9), twelfth thoracic vertebra (T12), third lumber vertebra (L3), and first sacral vertebra (S1) at regular intervals.