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Kinematic reconstruction of the spine with a regression model for load carriage study among soldiers

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1. Introduction

In a military context, knowledge of the mechanical behavior of the spine during soldiers' activities is essential to understanding the mechanism of load-carrying musculoskeletal disorders. To this end, it may be useful to consider an approach to the problem based on motion analysis, which requires numerical models capable of reproducing soldiers' movements. Various multi-body models of the spine have been developed to better understand the biomechanics of low back pain (Lerchl et al. 2023). However, the numerical fitting of these models requires spatial trajectories of reflective markers placed on the spine, which are occluded when the soldier is wearing a backpack. The aim of this study is to evaluate a multiple linear regression (MLR) approach used to reconstruct spine marker trajectories from visible markers that will not be occluded by wearing a backpack. The influence of using reconstructed markers on inverse kinematics results will be investigated.

2. Methods

2.1 Experiment

In a preliminary validity study, a motion capture experiment was carried out (Qualisys® system, 200Hz, 23 cameras). A volunteer participant (23-year-old male, h=1.90m, w=85kg) performed maximum spinal amplitude in each direction of motion: flexion-extension, lateral-bending and axial-rotation. This cycle was repeated 3 times at a slow pace and 3 times at a fast pace. The marker set used was a whole-body marker set comprising 49 markers placed according to ISB recommendations, and 9 additional markers were placed on the posterior processes of the vertebrae (C7, T1, T4, T5, T7, T8, T9, T12 and L1). A cluster of 6

markers was placed on the middle of the sternum to be used as an input of the reconstruction.

2.2 Human Models

The Twente spine model is an open-source, comprehensive and consistent subject-specific thoraco-lumbar model developed and validated by Bayoglu et al. (2019). It has been implemented in CusToM motion analysis library (Muller et al. 2019) and contains 17 vertebrae connected by ball joints (51 degrees of freedom). The implementation of kinematic constraints (Alemi et al. 2021) prevents unrealistic movements of the spine by allowing certain degrees of freedom (DoF) at intervertebral joints. The articular coordinates associated with these DoF, multiplied by a coefficient, are then associated with other intervertebral joints. This has led to the development of 7 models allowing from 3 to 9 degrees of freedom in the spine.

2.3 Multiple linear regression model

The coordinates of spinal markers that would be occluded were reconstructed from the visible markers: 4 head markers, 6 on the cluster, 1 on each acromioclavicular joint, 1 on the suprasternal notch, 1 on the xiphoid process and 1 on C7. Using a multiple linear regression (MLR) model ($fitlm(\mathbf{X}, \mathbf{Y})$ MATLAB function), the coefficients of the MLR matrix \mathbf{A} , its intersection \mathbf{B} and the residuals \mathbf{R} associated to the spine markers coordinates for each acquisition have been computed (Eq. 1). Concerning the inputs of this function, \mathbf{X} aggregates the visible marker coordinates and \mathbf{Y} aggregates the marker coordinates of the spine to reconstruct.

$$\mathbf{Y} = \mathbf{A} \mathbf{X} + \mathbf{B} + \mathbf{R} \quad (\text{Eq.1})$$

Occluded spine markers coordinates were then recomputed and used for an inverse kinematics calculation.

2.4 Evaluation

Inverse kinematics was computed using experimental markers (EXPE) on the one hand and reconstructed markers (RECO) on the other hand, for the fast-paced trials. Firstly, root mean squared error (RMSE) of kinematic reconstruction for spine markers was computed for each direction of motion and for each model to assess whether the use of RECO or the number of DoF of the model has an impact on the kinematic reconstruction of the spine. Secondly, to assess whether the use of RECO has an impact on overall spine angle, RMSE has been computed between spine angle computed using EXPE and RECO.

3. Results and discussion

Table 1: mean RMSE (mm) of kinematic reconstruction for spine markers using EXPE/RECO.

Model	Flexion-Extension	Lateral-Bending	Axial-Rotation
3 DoF	7.24 / 9.12	7.41 / 9.42	6.17 / 8.97
4 DoF	5.92 / 8.22	6.37 / 8.64	4.95 / 7.77
5 DoF	5.94 / 8.28	5.21 / 7.32	4.84 / 7.69
6 DoF	6.05 / 8.23	5.14 / 6.89	5.50 / 5.78
7 DoF	6.09 / 8.25	5.04 / 7.10	5.49 / 5.65
8 DoF	5.69 / 7.96	3.87 / 5.90	4.03 / 5.03
9 DoF	5.46 / 7.47	3.72 / 5.64	3.59 / 4.79

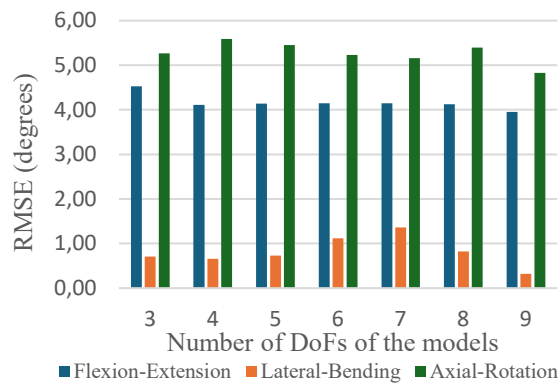


Figure 1: Mean RMSE (degrees) between overall spine angles computed using EXPE and RECO.

Kinematic reconstruction RMSE (Table 1) is systematically higher when RECO markers are used with an average increase of 36.3%. Furthermore, the reconstruction error tends to decrease with increasing number of DoF in the model, as in the study by Alemi et al. (2021), with a similar level of amplitude. Concerning the RMSE for overall spine angle (Figure 1), the use of RECO induces a higher mean RMSE for flexion-extension and axial-rotation than for lateral-flexion direction of motion. Moreover, the number of DoF does not affect the mean RMSE of overall spine angle. But intervertebral joint kinematics should be investigated in detail to assess the impact of the number of DoF of the model with the use of RECO. In this study, only one subject and only fast-paced trials were considered, making it difficult to assess the accuracy of the MLR method.

4. Conclusions

The aim of this study was to evaluate an MLR method for reconstructing the trajectories of spine markers, which would be occluded by a backpack. The results showed that the use of reconstructed markers for inverse kinematics induced an increase in kinematic reconstruction error and greater angular differences for flexion-extension and axial-rotation compared to

lateral-bending. The results remain acceptable but could be improved by adding markers on the anatomical landmarks of the spine, as well as technical markers to improve the reconstruction.

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Conflict of Interest Statement

The authors have no conflicting interests.

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