Journal of Biomechanics 43 (2010) 2043–2048

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Interpolation of segment Euler angles can provide a robust estimation of segment angular trajectories during asymmetric lifting tasks

Xu Xu[a,*], Chien-Chi Chang[b], Gert S. Faber[c], Idsart Kingma[c], Jack T. Dennerlein[a,d]

[a] *Department of Environmental Health, Harvard School of Public Health, 665 Huntington Avenue, Boston, MA 02115, USA*
[b] *Liberty Mutual Research Institute for Safety, 71 Frankland Road, Hopkinton, MA 01748, USA*
[c] *Institute for Fundamental and Clinical Human Movement Sciences, Faculty of Human Movement Sciences, Vrije Universiteit, Van der Boechorststraat 9, 1081 BT Amsterdam, The Netherlands*
[d] *Department of Orthopaedic Surgery, Brigham and Women's Hospital, Harvard Medical School, 75 Francis Street Boston, MA 02115, USA*

ARTICLE INFO

Article history:
Accepted 4 March 2010

Keywords:
3-D lifting
Cubic spline interpolation
Euler angles

ABSTRACT

Video-based field methods that estimate L5/S1 net joint moments from kinematics based on interpolation in the sagittal plane of joint angles alone can introduce a significant error on the interpolated joint angular trajectory when applied to asymmetric dynamic lifts. Our goal was to evaluate interpolation of segment Euler angles for a wide range of dynamic asymmetric lifting tasks using cubic spline methods by comparing the interpolated values with the continuous measured ones. For most body segments, the estimated trajectories of segment Euler angles have less than 5° RMSE (in each dimension) with 5-point cubic spline interpolation when there is no measurement error of interpolation points. Sensitivity analysis indicates that when the measurement error exists, the root mean square error (RMSE) of estimated trajectories increases. Comparison among different lifting conditions showed that lifting a load from a high initial position yielded a smaller RMSE than lifting from a low initial position. In conclusion, interpolation of segment Euler angles can provide a robust estimation of segment angular trajectories during asymmetric lifting when measurement error of interpolation points can be controlled at a low level.

1. Introduction

Using interpolation methods to generate a plausible continuous human movement from separate postures has been investigated in the fields of computer animation and virtual reality in the past decades (Hogfors et al., 1991; Badler et al., 1994; Rose et al., 1998; Mori and Hoshino, 2003; Busso et al., 2005). In ergonomics research, polynomial interpolation is used to obtain joint angular trajectories from coder-identified major joint angles of a few to several key video frames extracted from the side-view lifting video clips of the lifting task (Hsiang et al., 1998; Chang et al., 2003).

Side-view analysis of asymmetric lifting can result in large errors in L5/S1 joint location estimates (Kingma et al., 1998a). An interpolation of sagittal segment angles may not allow for an accurate rebuilding of the body movement for asymmetric lifting tasks. This may be problematic as lifting with twisting is associated with a higher risk of an acute prolapsed lumbar intervertebral disc (Kelsey et al., 1984; Marras et al., 1995) and can yield large lateral flexion and twisting torques and spine compression (Kingma et al., 1998b; Marras and Davis, 1998).

Our goal has been to develop a new method with interpolation to rebuild the body movement for asymmetric lifting tasks from a limited number of captured data points for a range of unconstrained dynamic lifting conditions. We compared estimated segment trajectories as obtained from interpolated Euler angles to three-dimensional (3-D) movement data under various asymmetric lifting tasks. The specific objectives were (1) to understand the relationship between interpolation errors on the trajectories of segment Euler angles and the number of the interpolation points, and (2) to investigate whether task variables such as load weight, initial height, and initial horizontal position, have significant effects on the segment Euler angles estimation.

2. Method

2.1. Procedure

Eleven male participants took part in the experiment (mean age 24.5 ± 4.7 years, mean height 183.3 ± 4.8 cm, mean weight 72.0 ± 9.1 kg). They performed an unconstrained lift with a box (50 cm wide, 35 cm deep and 30 cm high) by grabbing it symmetrically at its handles placed at a height of 27 cm on the box sides. The lift included walking toward the box, picking it up, and placing it on a

* Corresponding author. Tel.: +1 617 384 8768; fax: +1 617 384 8767.
E-mail address: xuxu0618@gmail.com (X. Xu).

0021-9290/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2010.03.010

table behind the participant. The lifting speed was not restricted and was chosen by the participants. Two load weights (9 and 15 kg), three initial horizontal distances (17.5, 37.5, and 57.5 cm), and two initial heights (floor and 96 cm) were examined. For each lifting condition, two repetitions were performed. A total of 24 lifts ($2 \times 3 \times 2 \times 2$) were performed by each participant in a random order. The experimental protocol was approved by the local ethics committee of VU University, Amsterdam.

2.2. Measurement

Three-dimensional body segment kinematics were measured with a sampling rate of 50 Hz by marker clusters, each containing three LED markers (Optotrak, Northern Digital, Waterloo, Canada) for the shanks, thighs, pelvis, trunk, upper arms, and forearms (Fig. 1).

Euler angles of body segments were calculated based on the rotation matrix from the anatomical coordinate system of each body segment to the global coordinate system. The anatomical axes system of each body segment was constructed using anatomical landmarks that had been digitized in an upright reference posture using a probe with 6 markers (Cappozzo et al., 1995). For the pelvis and trunk, anatomical axes were assumed to be aligned with the global axes during an upright standing reference posture. The global coordinate system is defined as follows: when the participant stands straight, facing the load to be lifted, positive X is to the front; positive Y is to the left; and positive Z is upward. The sequence of Euler angles decomposition is Y–X–Z (sagittal plane flexion–coronal plane flexion–transverse plane rotation). This sequence minimizes the possibility of the occurrence of gimbal lock so that it can only happen on the forearms.

2.3. Interpolation method and comparison

Cubic spline interpolations with different numbers of interpolation points were performed on each dimension of the Euler angles of each body segment during asymmetric lifting tasks. Cubic spline interpolation incurs less error than linear interpolation and does not have Runge's phenomenon (a strong oscillation at both ends of the interpolated curve) when compared with high order polynomial interpolation (Stoer and Bulirsch, 2002; Xu et al., 2010).

The starting time of the lift is defined as the instant of lift-off, and the ending time of the lift is defined as the trunk transverse plane rotation in the global axes reaching 90°. Two-point through 10-point cubic spline interpolation was performed for each dimension of segment Euler angles as described above (Matlab function interp1, The Mathworks, Natick, MA, USA). Equal time-spaced Euler angles of each body segment were selected to generate the cubic splines. For example, for 3-point interpolation on trunk movement, three points in each dimension of the Euler angles of the trunk were selected at time 0, $T/2$, T, while the total time for a lift is T, to generate the angular trajectory of the trunk with cubic spline interpolation (Fig. 2). If gimbal lock happened on a key frame used for the interpolation, the first rotation and the third rotation of the Euler angles were calculated by taking the average of the two frames that were previous to and following the gimbal lock frame. Thus, for each lift, 9 estimated angular trajectories were generated for each dimension of Euler angles for each body segment based on 2-point through 10-point cubic spline interpolation.

These 9 estimated segment angular trajectories were then compared with the measured trajectories. For each dimension of Euler angles, the root mean square error (RMSE) of estimated angular trajectories and the RMSE divided by the range of motion of the corresponding body segment (RMSE/RoM) were then calculated to quantify the accuracy of the estimation.

Fig. 1. Experiment setup for the lifting tasks. Marker clusters were used to monitor the movement of body segments.

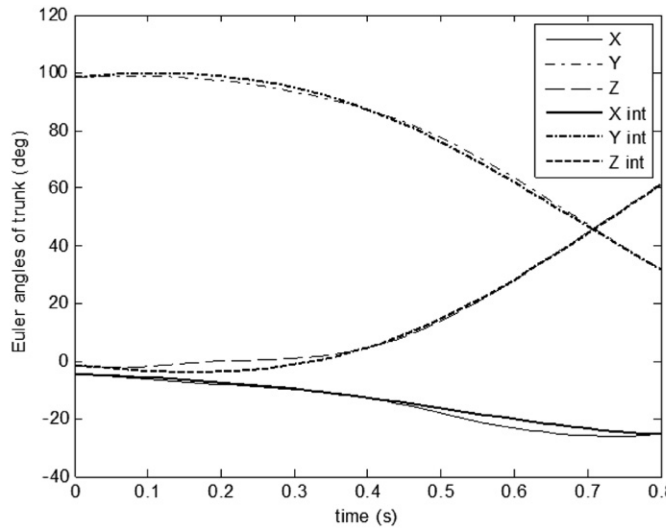

Fig. 2. An example (9 kg load weight, initial position 37.5 cm in front of the participant on the ground) of the measured Euler angles (thin lines) vs. Euler angles using 3-point interpolation (thick lines) for the trunk during a lifting task starting at the instant of lift-off and ending at the point of the lift where the twisting of the trunk reaches 90°. Since the participant rotated the trunk after lifting the box, the flexion angle of the trunk decreased and the rotation angle increased during the lift.

2.4. Data analysis

Analysis of Variance (ANOVA) was performed to test differences in RMSE and the RMSE/RoM of the estimated Euler angles across lifting conditions. The average of two repetitive lifts was calculated and entered into the ANOVA. All main effects and two-way interactions were included. The participants were treated as blocks. Since 2-, 5-, and 8-point cubic spline interpolation can represent rough, medium, and accurate segment Euler angles estimations, respectively, only the ANOVA for these interpolations was conducted for parsimony.

Errors can be introduced to the estimated angular trajectories not only by the algorithm of interpolation but also by the measurement errors of the interpolation points. For example, in the aforementioned video coding system (Hsiang et al., 1998; Chang et al., 2003), coder's observing error of joint angles in selected key frames is a measurement error. Therefore, a sensitivity analysis was applied to evaluate the effect of the measurement error of the interpolation points. For ranges of $\pm 2.5°$, $\pm 5°$, $\pm 10°$ and $\pm 15°$, a random error with uniform distribution was added to the interpolation point at each dimension of segment Euler angles. For each dimension of Euler angles, the RMSE of error-introduced angular trajectory was calculated.

3. Results

The interpolated Euler angles adequately follow the trend of the measured Euler angles (Fig. 2). The root mean square error (RMSE) and the root mean square error divided by the range of motion (RMSE/RoM) on each dimension of Euler angles reduces for all the participants when the number of the interpolation points increases (Fig. 3). With 5-point cubic spline interpolation, the estimated segment Euler angles have less than 5° RMSE for most body segments except forearms and have less than 0.1 RMSE/RoM (viz. 10% of RoM) for all body segments.

When the measurement error of interpolation points is induced, the RMSE of estimated angular trajectories increases (Fig. 4). The larger the measurement error induced, the larger the RMSE of estimated angular trajectories. For most body segments, when the error level reaches $\pm 10°$, increasing the number of