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Short communication

The error of L5/S1 joint moment calculation in a body-centered non-inertial reference frame when the fictitious force is ignored

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ABSTRACT

In ergonomics studies, linked segment models are commonly used for estimating dynamic L5/S1 joint moments during lifting tasks. The kinematics data input to these models are with respect to an arbitrary stationary reference frame. However, a body-centered reference frame, which is defined using the position and the orientation of human body segments, is sometimes used to conveniently identify the location of the load relative to the body. When a body-centered reference frame is moving with the body, it is a non-inertial reference frame and fictitious force exists. Directly applying a linked segment model to the kinematics data with respect to a body-centered non-inertial reference frame will ignore the effect of this fictitious force and introduce errors during L5/S1 moment estimation. In the current study, various lifting tasks were performed in the laboratory environment. The L5/S1 joint moments during the lifting tasks were calculated by a linked segment model with respect to a stationary reference frame and to a body-centered non-inertial reference frame. The results indicate that applying a linked segment model with respect to a body-centered non-inertial reference frame will result in overestimating the peak L5/S1 joint moments of the coronal plane, sagittal plane, and transverse plane during lifting tasks by 78%, 2%, and 59% on average, respectively. The instant when the peak moment occurred was delayed by 0.13, 0.03, and 0.09 s on average, correspondingly for the three planes. The root-mean-square errors of the L5/S1 joint moment for the three planes are 21 Nm, 19 Nm, and 9 Nm, correspondingly.

1. Introduction

Linked segment models have been used for estimating dynamic L5/S1 joint moments of various occupations (Chaffin, 1999; Kingma et al., 1996; Larivière and Gagnon, 1998; Shin and Mirka, 2004; Skotte, 2001; Skotte et al., 2002). The net moment at L5/S1 is expressed as (Hof, 1992; Plamondon et al., 1996):

$$\begin{aligned}\mathbf{M}_{L5/S1} = &-\sum_{a=1}^{p}[(\mathbf{r}_a-\mathbf{r}_{L5/S1})\times\mathbf{F}_a]-\sum_{b=1}^{q}\mathbf{M}_b\\&-\sum_{i=1}^{k}[(\mathbf{r}_i-\mathbf{r}_{L5/S1})\times m_i\mathbf{g}]\\&+\sum_{i=1}^{k}[(\mathbf{r}_i-\mathbf{r}_{L5/S1})\times m_i\mathbf{a}_i]+\sum_{i=1}^{k}d(\mathbf{I}_i\boldsymbol{\omega}_i)/dt \qquad (1)\end{aligned}$$

It should be noted that as Hof (1992) mentioned, the kinematics data used in Eq. (1) need to be defined with respect to a stationary reference frame. When a motion tracking system is used for kinematics data collection, the stationary reference frame can be arbitrarily defined on the ground.

A ground-fixed stationary reference frame, however, may not always be determined and sometimes a human body-centered reference frame is more convenient to use. For example, when a biomechanical model is reconstructed based on segment angles abstracted from the video frames, it could be hard to determine the positions, based on the video, of body segments relative to a ground-fixed stationary reference frame. Instead, one can conveniently define the origin of a body-centered reference frame at the mid-point between the ankles, one axis pointing upward, and one axis being perpendicular to the sagittal plane of neutral posture. Such a reference frame will be a stationary reference frame if foot positions are fixed and Eq. (1) still holds. The L5/S1 moment can then be estimated by the kinematics of each body segment based on the identified joint angular trajectories and anthropometry data (Chang et al., 2003; Hsiang et al., 1998). However, when foot movement or the rotation of the sagittal plane exists, such a body-centered reference frame will be a non-inertial reference frame and the effect of fictitious force needs to be considered when calculating L5/S1 moments (Jha, 2005).

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Nomenclature

$\mathbf{a}_i$	acceleration vector of segment i
$\mathbf{a}_o$	linear acceleration of origin of the non-inertial reference frame
$\mathbf{F}_a$	external force
$\mathbf{g}$	gravity vector
$\mathbf{I}_i$	moment of inertia of segment i
k	number of body segments involved in calculation
m	mass of point mass
m_i	mass of segment i
$\mathbf{M}_b$	external moment
$\mathbf{M}_{L5/S1}$	net moment of L5/S1 joint
p	number of external forces
q	number of external moments
$\mathbf{r}$	position vector of the point mass
$\mathbf{r}_a$	application position of $\mathbf{F}_a$
$\mathbf{r}_{L5/S1}$	position of L5/S1 joint
$\mathbf{v}_r$	speed of point mass with respect to the non-inertial reference frame
$\boldsymbol{\varepsilon}$	angular acceleration of the non-inertial reference frame
$\boldsymbol{\omega}$	angular velocity of the non-inertial reference frame
$\boldsymbol{\omega}_i$	angular velocity of segment i

In a non-inertial reference frame, the fictitious force on a point mass is written as (Jha, 2005):

$$\mathbf{F}_{fictitious} = m\mathbf{a}_o + m\boldsymbol{\varepsilon} \times \mathbf{r} + m\boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}) + 2m\boldsymbol{\omega} \times \mathbf{v}_r \tag{2}$$

On the right hand side of Eq. (2), the first term represents the fictitious force caused by linear acceleration of the non-inertial reference frame, the second term (a.k.a Euler force) represents the fictitious force caused by the rate of change of the angular velocity of non-inertial reference frame, and the third and the fourth terms (a.k.a centrifugal force and Coriolis force, respectively) represent the fictitious force caused by the angular velocity of the non-inertial reference frame.

In this study, we applied Eq. (1) to the kinematics data of lifting tasks with respect to a stationary reference frame as well as to a human body-centered non-inertial reference frame. Since Eq. (1) is with respect to a stationary reference frame, when it is applied to the kinematics data with respect to a non-inertial reference frame, the effect of fictitious force will be ignored. The goal of this study was to evaluate the amount of error introduced during 3-D L5/S1 joint moment calculation with respect to a body-centered non-inertial reference frame when the fictitious force is ignored.

2. Methods

2.1. Experimental procedure

The kinematic data of body segments and the external forces on hands during various lifting tasks were derived in previous studies (Faber et al., 2011; Xu et al., 2012). The experimental design is briefly described here for the readers' convenience. Eleven male participants were recruited (age: 24.5 ± 4.7 years, height: 1.83 ± 0.05 m, body mass: 72.0 ± 9.1 kg). During the experiment, the participants walked toward a box (50 cm wide, 35 cm deep and 30 cm high), grabbed the box symmetrically at its handles, picked the box up, and placed the box on a table about 2 m behind the participants. The lifting pattern and speed were unconstrained. Two levels of load weights (9 kg and 15 kg), three levels of initial horizontal distances (17.5 cm 37.5 cm, and 57.5 cm), and two levels of initial heights (floor and 96 cm) were examined. For each lifting condition, two repetitions were performed. Therefore, each participant performed 24 lift conditions ($2 \times 3 \times 2 \times 2$) in a randomized order. After the study was explained to the participants, written informed consent was obtained. The experimental protocol was approved by the institutional review board of VU University, Amsterdam.

2.2. Measurement

Six marker clusters, each containing three LEDs, were mounted with straps on the pelvis, trunk, arms, and forearms and were measured by the Optotrak motion tracking system (Northern Digital, Waterloo, Canada) at 50 Hz with respect to an arbitrary stationary reference frame (Faber et al., 2011; Xu et al., 2012). The anatomical reference frame of each body segment was constructed using anatomical landmarks that were digitized in an upright reference posture (Cappozzo et al., 1995). The external 3-D forces and moments on hands were collected by two strain-gauge based 6-axes force/moment sensors (MC3A, Advanced Mechanical Technology, Inc., Watertown, MA U.S.A.) which were attached to the handles of the box.

2.3. Data analysis

The body-centered reference frame was defined as the first axis pointed forward, parallel to the horizontal projection of the anterior–posterior axes of the pelvis, the second axis pointed upward and was perpendicular to the ground, and the third axis was perpendicular to the first and the second axes and oriented medio-laterally. The origin of the body-centered reference frame was the mid-point between the ankles. This way, the body-centered reference frame would approximately represent the orientation of the body. The kinematics data of each body segment were then transformed from the stationary reference frame to the body-centered reference frame.

The reference L5/S1 joint moments ($\mathbf{M}_{L5/S1}^{\mathrm{Ref}}$) were calculated by using a top-down method of a 3-D dynamic linked body segment model (Kingma et al., 1996), which essentially applied Eq. (1) with the kinematics data of the body segments above the L5/S1 joint (with respect to a stationary reference frame) as well as the external forces on hands. The L5/S1 moments with respect to the body-centered reference frame ($\mathbf{M}_{L5/S1}^{w/o\ \mathrm{fic}}$) were also calculated with the same model, but using the kinematics data with respect to the body-centered reference frame. Since Eq. (1) is with respect to a stationary reference frame, applying it to the kinematics data with respect to the body-centered non-inertial reference frame ignores the effect of fictitious force and results in L5/S1 moments without the components due to the fictitious force. Both $\mathbf{M}_{L5/S1}^{\mathrm{Ref}}$ and $\mathbf{M}_{L5/S1}^{w/o\ \mathrm{fic}}$ were then projected on the pelvic anatomical axes for improving anatomical interpretation.

The peak L5/S1 moments of the coronal plane, the sagittal plane, and the transverse plane, and the peak total L5/S1 moment (the peak value of the vector summation of the 3-D L5/S1 moment) for both $\mathbf{M}_{L5/S1}^{\mathrm{Ref}}$ and $\mathbf{M}_{L5/S1}^{w/o\ \mathrm{fic}}$ were extracted. A paired t-test was performed to examine whether ignoring the fictitious force would result in a significant difference on peak L5/S1 moments for each lifting condition. The time difference between the instants when the peak moments occurred was calculated and compared with zero by a t-test for each lifting condition as well. The root-mean-square (RMS) error for each lifting trial was also calculated to quantify the aggregated error of $\mathbf{M}_{L5/S1}^{w/o\ \mathrm{fic}}$ over the time.

3. Results

The results show that $\mathbf{M}_{L5/S1}^{w/o\ \mathrm{fic}}$ deviated from $\mathbf{M}_{L5/S1}^{\mathrm{Ref}}$ (Figs. 1 and 2). On average, across all lifting conditions, the peak $\mathbf{M}_{L5/S1}^{w/o\ \mathrm{fic}}$ of the coronal and transverse planes was increased by 78% and 59% of $\mathbf{M}_{L5/S1}^{\mathrm{Ref}}$ from 41 Nm and 16 Nm, respectively. The peak $\mathbf{M}_{L5/S1}^{w/o\ \mathrm{fic}}$ of the sagittal plane, however, only increased by 2% from 182 Nm. The peak total $\mathbf{M}_{L5/S1}^{w/o\ \mathrm{fic}}$ was 3% greater than the peak total $\mathbf{M}_{L5/S1}^{\mathrm{Ref}}$. The instant when the peak moment occurred was delayed by 0.13 ± 0.33, 0.03 ± 0.10, and 0.09 ± 0.28 s on average for the coronal, the sagittal, and the transverse planes, respectively. For the total moment, the instant of peak moment was delayed by 0.04 ± 0.13 s on average. The average RMS errors were 21 Nm, 19 Nm and 9 Nm for $\mathbf{M}_{L5/S1}^{w/o\ \mathrm{fic}}$ of the coronal, the sagittal, and the transverse planes, respectively, while the average RMS error for the total $\mathbf{M}_{L5/S1}^{w/o\ \mathrm{fic}}$ was 17 Nm.

The results of a number of paired t-tests indicate that the peak $\mathbf{M}_{L5/S1}^{w/o\ \mathrm{fic}}$ of the coronal plane and transverse plane was significantly

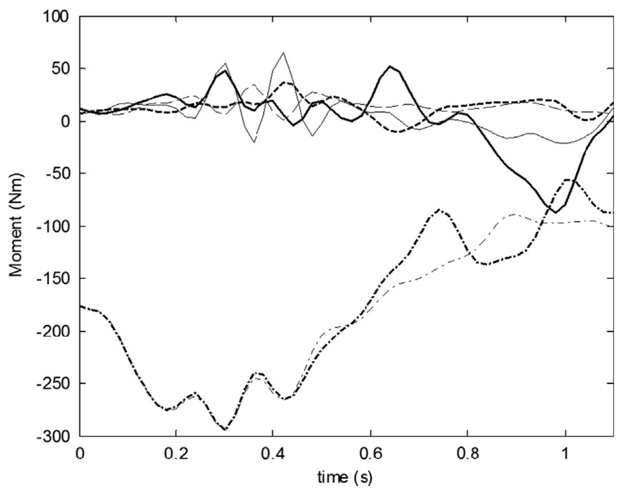

Fig. 1. An example (20 kg load weight, initial height at floor, 57.5 cm initial horizontal distance) of the reference L5/S1 moment (thin line) and the L5/S1 moment without the components due to the fictitious force (bold line). Solid lines represent the moment of the coronal plane, dash–dot lines represent the moment of the sagittal plane, and dashed lines represent the moment of the transverse plane.

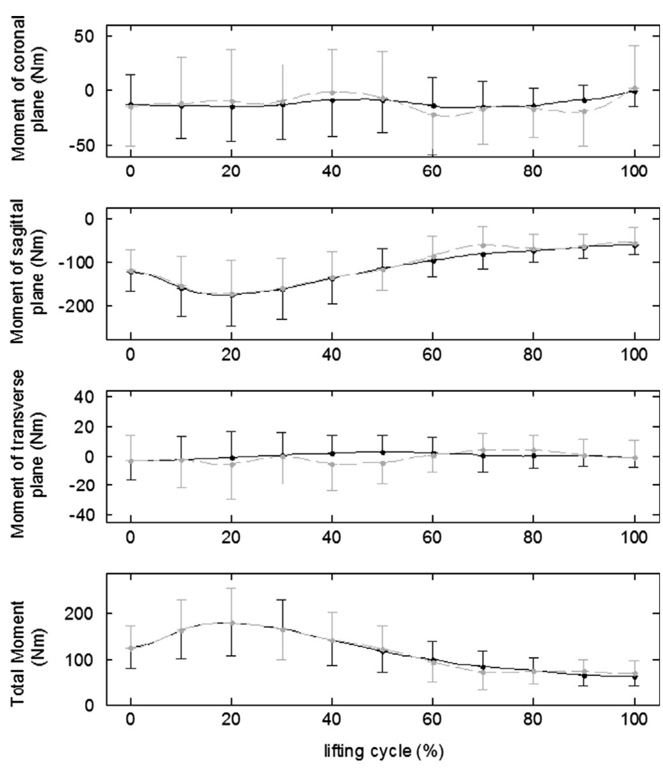

Fig. 2. The solid lines represent the average L5/S1 joint moments (the reference) based on the kinematics data in a stationary reference frame across all the lifting trials. The dashed lines represent the L5/S1 joint moments based on the kinematics data in a body-centered reference frame without considering the effect of the fictitious force. Error bars represent one-sided standard deviations.

increased for all lifting condition except for one compared with the corresponding peak $\mathbf{M}_{L5/S1}^{\mathrm{Ref}}$ (Table 1). The peak $\mathbf{M}_{L5/S1}^{w/o\ \mathrm{fic}}$ of the sagittal plane, however, was significantly increased for only four lifting conditions. The peak total $\mathbf{M}_{L5/S1}^{w/o\ \mathrm{fic}}$ was significantly increased for five lifting conditions. The results of *t*-tests for the time difference of peak moment revealed that the instant of peak moment of the coronal plane was significantly delayed for six lifting condition, and the instant of peak moment in the sagittal and the transverse plane was significantly delayed for three lifting conditions (Table 1).

4. Discussion

The results indicate that when ignoring the fictitious force in a body-centered reference frame, significant errors were introduced on peak and RMS L5/S1 joint moments and on the instant when the peak L5/S1 moment occurred.

In this study, the linear acceleration of the body-centered reference frame was caused by the foot movement as the origin of the body-centered reference frame was defined as the mid-point of the ankles. A further analysis (Fig. 3) indicates that the linear acceleration of the body-centered reference frame in the current study gradually increased during a lifting trial. At the beginning of a lifting trial, the foot movement was minimal so that the linear acceleration of the body-centered reference frame was low. After the participants grabbed the box, they usually stepped back with one foot while lifting the box up, and turned the trunk and moved the other foot to a position behind the first foot. During the foot movement, the origin of the body-centered reference frame kept moving with a varied velocity and resulted in a larger fictitious force due to the linear acceleration of the body-centered reference frame.

The centrifugal force and Coriolis force in the current study were caused by the rotation of the pelvis in the transverse plane as the orientation of the body-centered reference frame was determined by the anterior–posterior axis of the pelvis. The rotation of the pelvis was mainly observed when the upper body of the participants started to turn after the first foot stepped back. Therefore, the angular velocity of the body-centered reference frame was low at the beginning when the first foot was moving back without strong pelvic rotation (Fig. 3). As the pelvis did not rotate with a constant angular velocity, the angular acceleration of the body-centered reference frame existed and resulted in Euler force.

It should be noted that the magnitude of the fictitious forces is task-dependent. The lifting tasks performed in the current study probably generated substantial fictitious forces with respect to the body-centered reference frame since there was no restriction for the foot movement and the lifting tasks required a full body turning. In job settings that only require a lifter to lift a box from one position to another without foot movement, the total fictitious force is probably small. This is because no fictitious force due to foot movement would result when linear acceleration of the origin equals zero and the fictitious force due to the rotation of the body-centered reference frame would be minimized because the pelvis rotation of the transverse plane is constrained when the foot positions are fixed.

It should also be noted that the specific lifting tasks performed in the current study may limit the generalizability of the findings. The participants in this study usually lifted the box, stepped back, and turned the body. With such a movement pattern, the peak moment of the sagittal plane often occurs with stationary feet and is much greater than the moment error due to ignoring the fictitious force. Therefore, the peak moments of the sagittal plane were not significantly different for most of the lifting trials. This movement pattern also resulted in small moments of the transverse plane, both for the reference frame and the body-centered frame, which leads to minimum RMS error of the transverse plane. Moreover, the time difference between the instants when the peak moments occurred had a large variation over trials and participants, especially for the coronal and the transverse planes. This was probably due to variable patterns of stepping between

Table 1
Reference peak L5/S1 moments, the peak L5/S1 moment calculated in body-centered reference frame without considering fictitious force, the time difference between the instants when the peak moments occurred, and the RMS between the reference L5/S1 moment and the L5/S1 moment calculated in body-centered reference frame for each lifting conditions.

Load mass	Initial height	Initial horizontal distance	Coronal plane				Sagittal plane					Transverse plane					Total moment		
			Mean (SD) reference peak L5/S1 moment (Nm)	Mean (SD) peak L5/S1 moment without fictitious force (Nm)	Mean (SD) peak time difference (s)	Mean (SD) RMS (Nm)	Mean (SD) reference peak L5/S1 moment (Nm)	Mean (SD) peak L5/S1 moment without fictitious force (Nm)	Mean (SD) peak time difference (s)	Mean (SD) RMS (Nm)	Mean (SD) reference peak L5/S1 moment (Nm)	Mean (SD) peak L5/S1 moment without fictitious force (Nm)	Mean (SD) peak time difference (*s*)	Mean (SD) RMS (Nm)	Mean (SD) reference peak L5/S1 moment (Nm)	Mean (SD) peak L5/S1 moment without fictitious force (Nm)	Mean (SD) peak time difference (s)	Mean (SD) RMS (Nm)
9 kg	floor	17.5 cm	37 (18)	74 (23)*	0.04 (0.31)	19 (7)	207 (31)	207 (30)	−0.00 (0.01)	15 (5)	17 (6)	30 (15)*	0.19 (0.29)*	11 (4)	209 (31)	211 (31)	−0.01 (0.02)	14 (4)
		37.5 cm	35 (14)	70 (21)*	0.13 (0.43)	22 (9)	220 (40)	220 (39)	0.01 (0.02)	16 (6)	18 (10)	35 (21)*	−0.01 (0.23)	12 (5)	222 (40)	224 (39)	−0.00 (0.03)	14 (5)
		57.5 cm	35 (12)	78 (29)*	0.00 (0.33)	24 (14)	218 (34)	217 (33)	0.00 (0.01)	17 (7)	20 (11)	42 (27)*	0.01 (0.26)	13 (6)	220 (34)	225 (37)*	−0.00 (0.05)	16 (7)
	96 cm	17.5 cm	43 (23)	69 (22)*	0.23 (0.24)*	18 (5)	86 (17)	90 (17)	0.14 (0.15)*	20 (8)	14 (6)	18 (5)*	0.08 (0.18)	6 (2)	97 (18)	105 (14)*	0.18 (0.23)*	18 (7)
		37.5 cm	49 (21)	65 (23)*	0.22 (0.26)*	20 (5)	93 (19)	105 (19)*	0.09 (0.20)	24 (7)	14 (7)	21 (8)*	0.21 (0.22)*	6 (3)	106 (22)	112 (22)*	0.08 (0.13)	22 (6)
		57.5 cm	49 (31)	69 (25)*	0.21 (0.27)*	19 (5)	102 (17)	109 (25)	−0.01 (0.04)	19 (5)	14 (7)	20 (6)*	0.10 (0.19)	6 (2)	114 (26)	118 (28)	0.04 (0.17)	18 (5)
15 kg	floor	17.5 cm	37 (13)	77 (23)*	0.23 (0.34)*	23 (10)	247 (34)	246 (33)*	−0.00 (0.01)	16 (5)	23 (8)	38 (13)*	0.06 (0.28)	12 (6)	249 (34)	249 (34)	−0.00 (0.00)	15 (5)
		37.5 cm	33 (10)	74 (14)*	0.06 (0.31)	21 (5)	252 (43)	252 (43)	−0.00 (0.01)	17 (5)	25 (9)	37 (12)*	0.13 (0.22)*	11 (3)	254 (43)	254 (43)	−0.00 (0.00)	16 (5)
		57.5 cm	33 (8)	78 (34)*	0.19 (0.37)*	24 (15)	251 (40)	250 (40)	0.01 (0.04)	17 (5)	25 (13)	37 (21)*	0.02 (0.44)	10 (5)	252 (41)	253 (41)	0.01 (0.05)	17 (6)
	96 cm	17.5 cm	53 (23)	72 (24)*	0.13 (0.23)*	20 (5)	114 (21)	131 (23)*	0.10 (0.17)*	25 (6)	14 (5)	20 (7)*	0.04 (0.29)	7 (2)	125 (26)	140 (25)*	0.06 (0.14)	23 (6)
		37.5 cm	52 (25)	78 (25)*	0.10 (0.25)	23 (4)	111 (31)	131 (30)*	0.10 (0.13)*	25 (6)	16 (7)	23 (9)*	0.11 (0.23)	7 (2)	121 (35)	137 (31)*	0.15 (0.23)*	22 (6)
		57.5 cm	60 (38)	77 (30)	0.13 (0.27)	20 (6)	138 (45)	143 (47)	0.04 (0.09)	22 (7)	24 (23)	27 (19)	0.16 (0.28)	6 (2)	148 (51)	155 (51)	0.10 (0.18)	19 (5)
Overall			41 (22)	74 (25)*	0.13 (0.33)*	21 (9)	182 (72)	186 (67)*	0.03 (0.10)*	19 (7)	19 (11)	31 (18)*	0.09 (0.28)*	9 (5)	187 (69)	192 (66)*	0.04 (0.13)*	17 (6)

Asterisk indicates a statistically significant difference ($p < 0.05$).

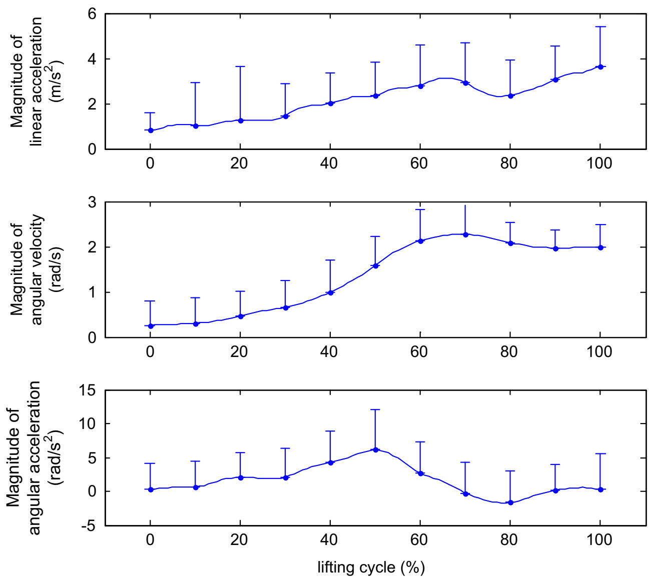

Fig. 3. Average linear acceleration of the origin, angular velocity, and angular acceleration of the body-centered reference frame across all the lifting trials. Error bars represent one-sided standard deviations.

participants and trials. If the lifting movement pattern changes, these findings can be altered.

There were a few other limitations of this study that need to be addressed. First, the selection of a body-centered reference frame in this study is arbitrary. If the origin and the orientation of a body-centered reference frame are based on different body segments, the magnitude and the direction of the fictitious force can be altered. Second, external forces on the hands were measured by transducers in the current study. If the external forces on the hands were estimated by hand acceleration and the mass of the box, then the estimated external forces would be altered when transferred from a stationary reference frame to a body-centered reference frame. This is because switching to a body-centered reference frame changes the kinematics of the hands, and would result in an additional error source when estimating the L5/S1 moment. Third, this study quantified only moments and not resulting spine forces. However, it is speculated that the effects of fictitious forces on compression and forward shear would likely be small during the lifting phase because peak moments of the sagittal plane occur mostly with stationary feet. The peak moments of the coronal and transverse planes occur during foot movement; therefore, the lateral shear forces are expected to be more affected. Fourth, only male participants performed the lifting tasks. Gender effects need to be further investigated.

In summary, with regards to lifting tasks as performed in the current study, it is advised against using a body-centered reference frame when peak moments of the coronal and transverse planes and their timing are of interest, as the relative errors are too large. For the moment of the sagittal plane, the problem seems small because the absolute moments are larger and the largest error is not likely to occur at the instant of peak moment.

Conflict of interest statement

All authors declare that there is no proprietary, financial, professional or other personal interest of any nature or kind in any product, service or company that could be construed as influencing the position presented in this manuscript.

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