Assessment of the Propagation of Uncertainty on Link Segment Model Results

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Link segment models are usually used to calculate proximal net reaction forces (PRF), as well as, proximal net moments (PNM). The correlation between electromyographic data and PNM is usually used to verify the model’s results. Nevertheless, this method permits only a qualitative verification of the obtained results. To assess model’s results in a quantitative perspective, another approach is needed. The aim of the current study was to assess the propagation of uncertainty on a link segment model results and identify the main sources of error on the quantification of PRF and PNM. One male performed five repetitions of different upper limb movements. An inverse dynamics approach associate with 3D link segment model was used to quantify PRF and PNM. The results of the model were evaluated by the use of Kleine and McClintock’s equation. The propagation of uncertainty for PRF reached, on average, 0.27 and for PNM, 0.97. The main cause of propagation of uncertainty was associated to the second time derivative calculations. Consequently, it is possible to suggest that the reduction of small distortions of center of mass acceleration will diminish the proximal net moment and proximal reaction force uncertainty values.

Keywords: biomechanics, kinetics, motion analysis, kinesiology

Several studies use link segment model for proximal net reaction forces (PRF), as well as, the proximal net moments (PNM) estimations (Feltner & Taylor, 1997; Fleisig, Andrews, Dillman, & Escamilla, 1995; Happee & Van der Helm, 1995; Sogaard, Laursen, Jensen, & Sjogaard, 2001). Link segment models are usually used to quantify overload applied to musculoskeletal system (Fleisig, Andrews, Dillman, & Escamilla, 1995). Like any model, biomechanical models also need to be validated.

Ideally, the results obtained by a biomechanical model should be compared with the measurement results of PRF and PNM in vivo (Nigg & Herzog, 1999). Considering technological and ethical issues, in vivo measurements are usually difficult to be done. Consequently, other methods are commonly sought for...
validating the models. Frequently, the results of the model are confronted with direct or indirect measurements (Nigg & Herzog, 1999). The literature has reported the following options for model results assessment: (1) accuracy of 3D reconstruction (Paul Allard, Stokes, & Blanchi, 1995); (2) quantitative comparison between partial results of the model and data obtained with another instrument (usually non invasive), for example: electrogoniometry x kinematics (Lavender & Rajulu, 1995; Nigg & Herzog, 1999); (3) qualitative comparison between partial results of the model and data obtained with another instrument, for example: PNM x EMG (Murray & Johnson, 2004).

Another option, to assess biomechanical model results, is to quantify the uncertainty or error associated to PRF and PNM calculations. Accordingly to Kleine (Holman, 1966), propagation of uncertainty (also called as propagation of error) is the effect of variables’ uncertainties (or errors) on the uncertainty of a function based on them. As far as our knowledge goes, we could not find a study which has quantified the uncertainty associated to PRF and PNM calculations for a 3D link segment model for the upper limb. The identification of potential source of errors at the model’s results would allow researchers to improve specific steps of collection and/or processing data. Therefore, the aim of the current study was to assess the propagation of uncertainty on a link segment model results and identify the main sources of error on the quantification of PRF and PNM.

Methods

One male, 25 years, 1.79 m and 80 kg performed five repetitions of different upper limb movements with his dominant arm. The input data for evaluation of the propagation of uncertainty is based on standard errors of: center of mass, segment mass; and errors associated with kinematics measurement (accuracy, temporal base error of each camera, linear regression method). Consequently, it is perfectly possible to classify these errors as systematic ones. As a result, we believe that to achieve the aim of the current study, the participation of only one subject does not weaken the present results.

The subject remained standing during the whole data collection with his opposite arm relaxed beside his trunk. The analyzed movements were the following: shoulder flexion, extension, abduction and horizontal flexion and elbow flexion. The subject had no history of injury on the evaluated upper limb. Approval for this study was obtained from the university ethics committee.

Kinematic data were collected using five digital video cameras (JVC GR-DVL 9800) with the shutter set in 1/250, frequency sample of 50 fields/sec. The software Dvideow (Figueroa, Leite, & Barros, 2003) was used for three-dimensional reconstruction. Further specifications about the software are described in the literature (Figueroa, et al., 2003). Image digitalization was performed by semiautomatic procedure with inverse, erosion and getmarkers algorithms (Figueroa, et al., 2003). After three-dimensional reconstruction, kinematic data were processed at the software Matlab 7.0 (Mathworks, Inc.), in which a biomechanical model of rigid segments was developed.

Anatomical references were determined by reflective spherical markers, with a diameter of 15 mm. The anatomical references used were: acromioclavicular
joint (AC), angulus acromialis (AA), angulus inferior (AI), glenohumeral center rotation (GH), incisura jugularis (IJ), lateral epycondile (LE), medial epycondile (ME), processus coracoideus (PC), processus spinosus of the eighteenth vertebra (T8), processus spinosus of the seventh cervical (C7), processus xiphoideus (PX), radial styloid (RS), sternoclavicular joint (SC), trigonum spinae scapulae (TS), ulnar styloid (US). The GH center of rotation was determined by the Regression Method (Meskers, van der Helm, Rozendaal, & Rozing, 1998). To avoid artifacts movements in ME and LE references, it was used a technical mark in the arm (Schmidt, Disselhorst-Klug, Silny, & Rau, 1999). The technical mark consisted of three noncollinear retro reflective markers fixed in a cuff, which was fixed at the subject’s arm. Anatomical references and local coordinate systems were defined as recommended by the International Society of Biomechanics (Wu, et al., 2005). The synchronism intracamaeras was performed by the audio band of the cameras (Barros, Russomanno, Brenzikover, & Figueroa, 2006).

The accuracy of measurements of the distance between the markers was assumed as representative of the system measurement errors (Sarro, Silvatti, Aliverti, & Barros, 2009). Two retro reflective spherical markers were fixed to a rigid bar moving on a calibrated volume of approximately $1.262 \times 1.082 \times 0.902$ m$^3$. The measurement between the markers (231.5 mm) was obtained by the use of a caliper (with 0.05 mm of resolution) and was assumed to be the real value. The accuracy was calculated as follows:

$$a^2 = b^2 + p^2$$

Where:

- $a$ = accuracy;
- $b^2$ = variance of experimental data;
- $b$ = bias, given by the difference between the mean value (experimental measurement) and the real value (direct measurement).

The dynamic analysis were performed by one link segment model (Ribeiro, 2006). The model is governed by Newton-Euler movement equations (Praagman, Stokdijk, Veeger, & Visser, 2000; Winter, 2005; Zatsiorsky, 2002). Equations (2–3) and (4–5) govern linear and angular movement, respectively.

$$\sum F = m.a$$

Detailing the sum of forces results in the following equation:

$$PRF + DRF + S_w = m.a$$

Where:

- $m$ = mass;
- $a$ = acceleration of the center of mass of the segment;
- PRF = proximal reaction force;
- DRF = distal reaction force;
- $S_w$ = segment weight;

$$\sum M = \dot{H}$$
Detailing the sum of moments results in the following Equation (5):

\[
MPRF + MDRF + PNM + DNM = \dot{H}
\]  

(5)

Where:

\( \dot{H} \) = time rate of the angular momentum of the segment;

Kinematic, kinetic, and anthropometric data are independent variables of the model; the dependent variables are PRF and PNM (Praagman, et al., 2000; Vaughan, Davis, & O’connor, 1999). Body segment parameters were calculated using anthropometric data described by Zatsiorsky (2002) and adjusted as described by de Leva (1996).

Movement trials were performed in two different stages. During the first stage the subject, in a rest position, was filmed. This enables to digitalize all reflective points (AC, AA, AI, GH, IJ, EL, EM, PC, T8, C7, PX, RS, SC, TS, US). In the second stage, the subject performed five repetitions of each movement cited previously. The subject performed five executions of each movement, with a mean angular speed of 45°/s monitored by a metronome.

Kinematic data were filtered with a digital filter butterworth, 3th order. The cut-off frequency was determined by Residual Analysis Method (Winter, 2005) and ranged from 0.5 to 4.9 Hz. It was calculated the uncertainty extended through the PRF and PNM calculations. The goal was to verify the influence of small measurement distortions on PRF and PNM final magnitudes. For that, we have used the method proposed by Kleine and McClintock (Holman, 1966). Assuming “y” as a function of “n” independent variables (Equation 6) and that “y” uncertainty presents a Gaussian pattern, the uncertainty could be quantified as following:

\[
y = f(x_1, x_2, x_3, ..., x_n)
\]  

(6)

\[
u_y = \pm \sqrt{\left( \frac{\partial y}{\partial x_1} \Delta x_1 \right)^2 + \left( \frac{\partial y}{\partial x_2} \Delta x_2 \right)^2 + ... + \left( \frac{\partial y}{\partial x_n} \Delta x_n \right)^2}
\]  

(7)

Where:

\( y \) = function of “n” independent variables;

\( x_n \) = nth independent variable;

\( \Delta x_n \) = uncertainty of the nth independent variable;

\( u_y \) = uncertainty of \( y \);

The uncertainty was quantified for PRF and PNM of the wrist, elbow and shoulder. For linear movement equations, the propagation of uncertainty was calculated for all variables involved on the equations. For angular movement equations, the analysis was simplified. Since inertial contribution to PNM magnitude was close to zero Nm, due to the low angular speed, the propagation of uncertainty was calculated only with the other variables: distal reaction moment (DRM); moment caused by distal reaction force (MDRF); and moment caused by proximal reaction force (MPRF). Due to the slow angular speed the movement was performed, + presented
values below 0.005 Nm. Even possible amplifications due to second derivatives calculations were not enough to make it an important source of uncertainty. When analyzing more complex and faster movements, the inertial contribution to PNM should be taken into account.

Equation (7) can only be applied if the uncertainty associated with each variable is known. Consequently, the following values were adopted:

- The uncertainty associated with digitalization process was equivalent to the accuracy of video-based system (1.7 mm);
- The uncertainty associated with anthropometric predictions data were equivalent to its standard error (Zatsiorsky, 2002). Those uncertainties were calculated for each segment (hand, forearm and arm);
- The uncertainty associated with the temporal base of each camera was equal to 4 μs, the same as found by other authors (Barros, et al., 2006);
- The uncertainty associated with the Linear Regression Method was 4.91 mm (Meskers, et al., 1998).

The uncertainty associated with all the others variables of linear and angular movement equations were calculated. The steps adopted are presented in Figure 1. Because it was used a link segment model associated to inverse dynamics solutions, it is needed to assess propagation of uncertainty for the PRF for each segment. The calculation is performed in the following segment sequence: hand, forearm and arm. The same sequence is used for PNM\textsubscript{U}.

Assuming PRF as a function of the following variables: mass, acceleration of the segment and distal force; it is possible to write PRF in the Equation (6) format, according to Equation (8):

\[
PRF = f (m, a, DRF)
\]  

Where:

- PRF = proximal reaction force;
- m = mass;
- a = acceleration;
- DRF = distal reaction force;

To calculate PRF\textsubscript{U}, the following variables need to be known: mass uncertainty (mass\textsubscript{U}), acceleration uncertainty (Accel\textsubscript{U}), distal reaction force uncertainty (DRF\textsubscript{U}). Consequently, the following Equations (9 and 10) must be applied.

The acceleration of the segment is dependent on the position of the center of mass. The Equation which defines Accel\textsubscript{U} is the following (9):

\[
Accel\textsubscript{U} = \pm \sqrt{\left(\frac{\partial Accel}{\partial \Delta p_1} \Delta p_1\right)^2 + \left(\frac{\partial Accel}{\partial \Delta p_2} \Delta p_2\right)^2 + \left(\frac{\partial Accel}{\partial \Delta p_3} \Delta p_3\right)^2}
\]  

Where:

- Accel\textsubscript{U} = acceleration uncertainty;
- \Delta p = uncertainty of position (1, 2 or 3);
- \partial = derivative function of position (1, 2 or 3);
Consequently, applying Equation (7), results in the following Equation (10):

$$PRFU = \pm \sqrt{\left(\frac{\partial PRF}{\partial m} \Delta m \right)^2 + \left(\frac{\partial PRF}{\partial a} \Delta a \right)^2 + \left(\frac{\partial PRF}{\partial DRF} \Delta DRF \right)^2}$$  \quad (10)$$

Where:

- $PRFU$ = proximal reaction force uncertainty;
- $PRF$ = proximal reaction force;
- $m$ = mass;
- $a$ = acceleration;
- $mU$ = mass uncertainty;
- $aU$ = acceleration uncertainty;
- $M$ = moment;
- $I$ = inertial moment;
- $\alpha$ = angular speed;
- $MPRF = moment caused by proximal reaction force$;
- $MDRF = moment caused by distal reaction force$;
- $DRM = distal reaction moment$;
- $MPRFU = moment caused by proximal reaction force uncertainty$;
- $MDRFU = moment caused by distal reaction force uncertainty$;
- $DRMU = distal reaction moment uncertainty$.

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**Figure 1** — Assessment of propagation of uncertainty during the whole data processing steps on the link segment model calculations: (a) Proximal Reaction Force (PRF) and (b) Proximal Net Moment (PNM). $m$ = mass; $a$ = acceleration; $DRF$ = distal reaction force; $mU$ = mass uncertainty; $AccelU$ = acceleration uncertainty; $M$ = moment; $I$ = inertial moment; $\alpha$ = angular speed; $MPRF$ = moment caused by proximal reaction force; $MDRF$ = moment caused by distal reaction force; $DRM = distal reaction moment$; $MPRFU = moment caused by proximal reaction force uncertainty$; $MDRFU = moment caused by distal reaction force uncertainty$; $DRMU = distal reaction moment uncertainty$. 
Assessment of Link Segment Model Results

$\text{DRF} = \text{distal reaction force;}
\partial_{\text{PRF}} = \text{derivative function of PRF;}
\partial^\alpha = \text{derivative function of acceleration;}
\partial_{\text{DRF}} = \text{derivative function of distal force;}
\Delta_m = \text{uncertainty of mass;}
\Delta_a = \text{uncertainty of acceleration;}
\Delta_{\text{DRF}} = \text{uncertainty of distal reaction force;}
$

Because the current study analyzed a 3D link segment model governed by Newton-Euler movement equations, it was necessary to apply Equation (10) for each segment, in the following order: hand, forearm and arm. Considering the hand segment, the variables $D_f, \partial D_f, \Delta D_f$ will value zero, since there is no distal force being applied to the hand.

Considering that $\text{PNM}$ is a function of the following variables: moment caused by distal reaction force ($\text{MDRF}$); and moment caused by proximal reaction force ($\text{MPRF}$); applying Equation (6) in this case results in Equation (11):

$$\text{PNM} = f (\text{MDRF}, \text{MPRF}, \text{DRM}) \quad (11)$$

Where:

- $\text{MPRF} = \text{moment caused by proximal reaction force;}
- \text{MDRF} = \text{moment caused by distal reaction force;}
- \text{DRM} = \text{distal reaction moment;}
$

To calculate $\text{PNMU}$, the following variables need to be known: $\text{MPRFU}, \text{MDRFU}, \text{DRMU}$. Consequently, the following Equation 12 must be applied.

The $\text{MPRF}$ of the segment is dependent on: the position of the center of mass, proximal axis of rotation and PRF. The Equation which defines $\text{MPRFU}$ is the following (12):

$$\text{MPRFU} = \pm \sqrt{\left(\frac{\partial_{\text{MPRF}}}{\partial_{\text{cm}}} \Delta_{\text{cm}}\right)^2 + \left(\frac{\partial_{\text{MPRF}}}{\partial_{\text{par}}} \Delta_{\text{par}}\right)^2 + \left(\frac{\partial_{\text{MPRF}}}{\partial_{\text{PRF}}} \Delta_{\text{PRF}}\right)^2} \quad (12)$$

Where:

- $\text{MPRFU} = \text{moment caused by proximal reaction force uncertainty;}
- \text{cm} = \text{center of mass;}
- \text{PRF} = \text{proximal reaction force;}
- \text{par} = \text{proximal axis of rotation;}
- \partial_{\text{PRF}} = \text{derivative function of PRF;}
- \partial_{\text{cm}} = \text{derivative function of center of mass;}
- \partial_{\text{par}} = \text{derivative function of proximal axis of rotation;}
- \Delta_m = \text{uncertainty of center of mass;}
- \Delta_{\text{par}} = \text{uncertainty of proximal axis of rotation;}
- \Delta_{\text{PRF}} = \text{uncertainty of proximal reaction force;}
$
Results

The video-based system accuracy, bias and precision were 1.7 mm, 0.5 mm, and 1.6 mm, respectively. The PRF and PNM uncertainties were calculated for all joint (wrist, elbow and shoulder). Nonetheless, the following results of PRF uncertainty (PRFU) and PNM uncertainty (PNMU) refer only to shoulder joint (for abduction, flexion, extension and horizontal flexion movements) or elbow (for elbow flexion movement). The PRFU differed accordingly to the analyzed movement (Table 1). The highest PRFU/PRF ratio (0.30) was associated with the elbow flexion. The smallest PRFU/PRF ratio (0.25) was related to shoulder abduction and extension movements. During shoulder flexion, the PRFU/PRF ratio was 0.26; and during horizontal flexion the PRFU/PRF ratio was 0.29.

The PNM uncertainty (PNMU) for shoulder movements presented a range of 0.78–1.53 (Table 1). The largest PNMU/PNM ratio was found for shoulder extension (1.53). The smallest PNMU/PNM ratio was found for horizontal flexion of the shoulder (0.78). Shoulder abduction and flexion movements presented a PNMU/PNM ratio of 0.91 and 1.11, respectively. On the other hand, during elbow flexion, the PNMU/PNM ratio was 0.17.

PRFU is caused by innumerous small distortions and errors associated to other variables. Consequently, if we analyze the contributions of all those variables to the uncertainty magnitude, it is possible to identify which variable is the major responsible to PRFU magnitude. The contribution of mass uncertainty (MassU), acceleration uncertainty (AccelU), distal reaction force uncertainty (DRFU), and weight uncertainty (WeightU) on PRFU is presented on Table 2. The contribution of MassU and WeightU represents zero percent to total PRFU. In contrast, the larger

Table 1  Mean and standard deviation values of proximal reaction force (PRF), proximal net moment (PNM), PRF uncertainty (PRFU) and PNM uncertainty (PNMU) for different analyzed movements.

<table>
<thead>
<tr>
<th>Movement</th>
<th>Shoulder Abduction</th>
<th>Shoulder Flexion</th>
<th>Shoulder Extension</th>
<th>Horizontal Flexion</th>
<th>Elbow Flexion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean PRF (N)</td>
<td>38.8</td>
<td>38.8</td>
<td>38.9</td>
<td>38.8</td>
<td>17.6</td>
</tr>
<tr>
<td>±1.4</td>
<td>±1.8</td>
<td>±1.3</td>
<td>±0.9</td>
<td>±0.6</td>
<td></td>
</tr>
<tr>
<td>Mean PRFU (N)</td>
<td>9.8</td>
<td>10.0</td>
<td>9.8</td>
<td>11.1</td>
<td>5.2</td>
</tr>
<tr>
<td>±0.3</td>
<td>±0.8</td>
<td>±0.4</td>
<td>±0.8</td>
<td>±0.2</td>
<td></td>
</tr>
<tr>
<td>PRFU/PRF</td>
<td>0.25</td>
<td>0.26</td>
<td>0.25</td>
<td>0.29</td>
<td>0.30</td>
</tr>
<tr>
<td>Mean PNM (Nm)</td>
<td>6.6</td>
<td>5.7</td>
<td>3.5</td>
<td>10.2</td>
<td>2.0</td>
</tr>
<tr>
<td>±2.9</td>
<td>±2.7</td>
<td>±1.2</td>
<td>±0.6</td>
<td>±0.6</td>
<td></td>
</tr>
<tr>
<td>Mean PNMU (N)</td>
<td>6.0</td>
<td>6.3</td>
<td>5.3</td>
<td>8.0</td>
<td>0.3</td>
</tr>
<tr>
<td>±0.8</td>
<td>±1.1</td>
<td>±0.2</td>
<td>±0.8</td>
<td>±0.2</td>
<td></td>
</tr>
<tr>
<td>PNMU/PNM</td>
<td>0.91</td>
<td>1.11</td>
<td>1.53</td>
<td>0.78</td>
<td>0.17</td>
</tr>
</tbody>
</table>
values of mean Accel\(U\) and mean DRF\(U\) represented 73.2\% (for shoulder extension movement) and 39.5\% (for flexion elbow movement) of total PRF\(U\), respectively. Mean Accel\(U\) and mean DRF\(U\) fluctuated accordingly to the analyzed movements.

The contributions of all variables to final PNM\(U\) are presented on Table 3. As stated before, since inertial contributions to PNM were zero, we have assumed that the former would not propagate any error on the latter calculations. Therefore, the only variables that contribute to PNM\(U\) are: moment caused by distal reaction force (MDRF), moment caused by proximal reaction force (MPRF) and distal reaction moment (DRM).

### Table 2  Mean and standard deviation contribution (\%) of different variables on PRFU.

<table>
<thead>
<tr>
<th>Movement</th>
<th>Shoulder</th>
<th>Elbow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Abduction</td>
<td>Flexion</td>
</tr>
<tr>
<td>Mean Mass(U)</td>
<td>0.0 (\pm 0.0)</td>
<td>0.0 (\pm 0.0)</td>
</tr>
<tr>
<td>Mean Accel(U)</td>
<td>60.6 (\pm 2.9)</td>
<td>61.7 (\pm 5.3)</td>
</tr>
<tr>
<td>Mean DRF(U)</td>
<td>39.4 (\pm 2.3)</td>
<td>38.3 (\pm 2.3)</td>
</tr>
<tr>
<td>Mean Weight(U)</td>
<td>0.0 (\pm 0.0)</td>
<td>0.0 (\pm 0.0)</td>
</tr>
</tbody>
</table>

PRFU: proximal reaction force uncertainty; Mass\(U\): mass uncertainty; Accel\(U\): acceleration uncertainty; DRFU: distal reaction force uncertainty; Weight\(U\): weight uncertainty.

### Table 3  Mean and standard deviation contribution (\%) of all variables to PNM\(U\).

<table>
<thead>
<tr>
<th>Movement</th>
<th>Shoulder</th>
<th>Elbow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Abduction</td>
<td>Flexion</td>
</tr>
<tr>
<td>Mean MDRFU</td>
<td>77.0 (\pm 7.8)</td>
<td>73.2 (\pm 8.8)</td>
</tr>
<tr>
<td>Mean MPRFU</td>
<td>18.3 (\pm 15.7)</td>
<td>22.4 (\pm 17.6)</td>
</tr>
<tr>
<td>Mean MDU</td>
<td>4.7 (\pm 3.2)</td>
<td>4.4 (\pm 3.2)</td>
</tr>
</tbody>
</table>

PNMU: proximal net moment uncertainty; MDRFU: distal reaction force moment uncertainty; PRFMU: proximal reaction force moment uncertainty; MDU: distal reaction moment uncertainty.
Discussion

The propagation of errors during the different steps taken during reconstruction of three-dimensional coordinates is well known (P. Allard, Blanchi, & Aïssaoui, 1995a; Gruen, 1997). The major factors that influence the quality of the reconstructed coordinates are: imaging device, marker identification, camera setup, and calibration (P. Allard, et al., 1995a). In the current study, the accuracy of the video-based system was, on average, 1.7 mm—the same value found by other authors (Gruen, 1997). Barros et al. (2006) found an accuracy of 2.65 mm using the same software for 3D reconstruction. The precision mean value found in the current study was 1.6 mm. It is stated that 3 mm of precision value is considered acceptable (Pascoal & Van der Helm, 2001). Therefore, the video-based system errors found in the current study are within the accepted values reported in the literature and we can assume that, because of accuracy values, it is not necessary to focus efforts to improve 3D reconstruction coordinate data.

Although commonly assumed as accurate and reproducible methods, the main causes of potential inaccuracies of inverse dynamics solutions are: displacement of the skin markers with respect to the skeleton, difficulties in determining the acceleration of the marker from their known position, difficulties in locating the joint axes of rotation, inaccuracy on determining body-segment parameters, and inaccuracy on determining the point of application of external forces, specially the ground reaction forces (Zatsiorsky, 2002). Because, accordingly to our results, the two main variables that contribute to PFR\textsubscript{U} are Accel\textsubscript{U} and DRF\textsubscript{U}, it is evident that the propagation of uncertainty is caused mainly by second time derivative of center of mass (CoM) position. Since all movements analyzed are performed in opened kinetic chain, DRF\textsubscript{U} is, as well, mainly caused by the second time derivative (Zatsiorsky, 2002). On the beginning of kinetic calculations, there is no DRF applied on the hand segment. Therefore, PRF of the hand segment is equal to the product of mass and acceleration of that segment. The PRF of the hand will be equivalent to the DRF of the forearm. The same will proceed to the arm, when PRF of the forearm is converted to DRF of the former segment. As a result, there will be a propagation of the Accel\textsubscript{U} of CoM of the hand on PRF and DRF values. Consequently, a logical solution to reduce PRF\textsubscript{U} is to minimize possible distortions caused by second time differentiation. Other authors also found problems associated with second time derivatives (Hong, Cheung, & Roberts, 2001; Rodgers, Tummarakota, & Lieh, 1998). The differentiation process leads to a signal noise-amplification. The higher the frequency components in a position signal, the higher noise amplification on velocity, acceleration, and higher derivatives (Woltring, 1995). On link segment models, systematic errors in measurement devices and modeling errors have propagation effects on data processing chain, amplifying final results noise (Rodgers, et al., 1998; Woltring, 1995). One possible solution seems to be the increase of frequency sample (Woltring, 1995).

The major contributor to PNM\textsubscript{U}, during shoulder movements, was the MDRF variable (Table 3). Conversely, for elbow flexion, the main contribution to PNM\textsubscript{U} was associated with MPRF (60.8%). Evidently, the uncertainty magnitude of MDRF and MPRF are caused mainly by the derivatives problems as cited before, as well as for the DRF and PRF. Because MDRF and MPRF are the moment caused by these forces (DRF and PRF, respectively), it is reasonable to expect larger uncertainties
associated with MDRF and MPRF. More accurate calculations of accelerations will result on smaller PNM\textsubscript{U}.

There are limitations to this study. Firstly, the scapula was monitored with the use of surface markers. Undoubtedly, some error of measurement will arise from it. Unfortunately, we cannot precise the magnitude of error related to it. As a result, the propagation of uncertainty might be slightly higher than the results found in the current study. It is important to highlight that the most significant source of uncertainty is associated with second time derivative of center of mass. As a result, the uncertainty associated with the scapular surface markers will not have a relevant impact on our results. Besides, the GH center of rotation was shown to follow the AA marker, throughout all movement executions. Consequently, we can assume that the GH center of rotation was, relatively, well represented by the use of the linear regression method. Secondly, all calculations for propagation of uncertainty were made in absolute values, consequently, there is no distinction for the uncertainty related to X, Y or Z components of those variables. It is possible that there could be different uncertainty magnitudes, accordingly to each component. However, the main goal of the current study was to measure the propagation of uncertainty during the whole data processing steps. The present evaluation of biomechanical models allows identifying where the focus of possible miscalculations is located and permits the researcher to adapt methodological issues to improve it.

It was presented an assessment of the propagation of uncertainty for proximal net moment and proximal reaction force. The propagation of uncertainty for proximal reaction forces reached, on average, 0.27 and for proximal net moments, 0.97. The second time derivative calculations seems to be one of the major causes of the propagation of uncertainty magnitudes, therefore, reducing small distortions of center of mass acceleration will probably diminish the proximal net moment and proximal reaction force uncertainties.

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References


