Accuracy and reliability of a low-cost methodology to assess 3D body posture based on commercial cameras and Excel templates.

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Highlights

The low-cost methodology allows to obtain postural parameters with good accuracy.

It also showed high reliability, both inter-rater and intra-rater.

It is user-friendly and does not require mathematical or programming knowledge.

It allows obtaining a value of the error of measurement in real units.

Abstract

Analysing body posture in 3D generally requires expensive equipment and complex software, not accessible to most healthcare centres. The aim of this work is to evaluate a 3D postural analysis methodology based on commercial cameras, a portable calibration device and templates developed in Microsoft Excel, a popular spreadsheet software. The accuracy and reliability of the methodology were studied using a 3D optical motion capture system with submillimetre accuracy as reference. For that, 99 length and 99 angular anthropometrics parameters of 9 subjects were measured and Pearson's r , Lin's concordance correlation coefficient (Lin's CCC), root mean square error, mean absolute error and Bland Altman graphs were computed. The measurement errors were of approximately 2 mm and of 1-2 degrees, and the methodology was very reliable (Lin's CCC was above 0.99 in all cases). The suggested methodology could be used for applied 3D postural studies, where usually submillimetre accuracy is not required.

Keywords: Stereophotogrammetry, Videography, Image Processing, Bioinformatics, Anthropometry.

1. Introduction

3D optoelectronic motion capture (OMC) systems are not used by physical therapists and other healthcare specialists due to time required for testing, their expensive price and for the data analysis time cost, which sometimes requires the use of an additional biomechanics software (such as Visual 3D). There are free solutions to perform this type of analysis such as Check 3D (Sheffield University, UK) [1] or SkillSpector (Video4coach, Denmark) [2,3]. Check 3D is a software that allows to perform the camera calibration using a chessboard; subsequently, the 2D coordinates in pixels are digitized in two cameras and the software provides a comma-separated values (CSV) file with the 3D coordinates of the markers. SkillSpector is a software that works for both Macintosh (Apple Inc.) and Windows (Microsoft) environments and allows to calibrate the cameras using a calibration frame and applying the Direct Linear Transformation (DLT) algorithm. Despite the fact that all these softwares are free, healthcare professionals require direct solutions to analyse posture as to optimize time of the patient's visit.

There are low-cost alternatives to traditional photogrammetry, such as some based on the Microsoft Kinect camera (Microsoft Corporation, Redmond, USA). However, most of these systems have not yet achieved sufficient accuracy to measure anthropometric parameters in postural studies that require high precision. For example, Tong et al. [4] or Plantard et al. [5] found an error of biometric measures greater than 1 cm or more than 5 degrees [5]. Even though these systems can estimate the position of large joint centres with a certain precision [6] they will hardly be able to detect less evident anatomical points (such as the scapular processes). Systems based on IMUs could also be an alternative to measure postural parameters, as they are increasingly accurate [7–9]. However, further technological development is still required to measure the position of less noticeable anatomical points (such as those of the scapula).

3D reconstruction can be performed with the aforementioned DLT algorithm. It was developed in 1971 [10] and continues to be widely used in 3D analysis software such as SimiMotion (SIMI Reality Motion Systems GmbH, Germany), Kwon3D (Visol Inc., Korea) or Ariel Performance Analysis System (APAS, ARIEL Dynamics, Trabuco Canyon, CA, USA). The algorithm has been

implemented in different mathematical analysis software such as Matlab [11,12], GNU Octave [12], R [13] or Python [14]. Despite the fact that Microsoft Excel is one of the most widely used mathematical software, we have not found online Excel templates that allows 3D marker reconstruction and postural analysis. Another problem with the DLT algorithm is that the devices required to perform the calibration (calibration frames) are usually bulky and sometimes there is no physical space in clinics or research centres [15].

The objective of the present work is therefore to develop Microsoft Excel templates for reconstructing marker 3D position and analysing posture in 3D. It implements the DLT algorithm, and generates posturographic reports semi-automatically. The methodology is based on commercial cameras and a portable calibration device. The accuracy of the aforementioned methodology (including sources of errors such as camera position, calibration frame and software used to perform the 2D digitization) will be studied using a 3D OMC system with submillimetre accuracy (Qualisys) as the *gold standard*. The handling of the Excel sheet will be explained in detail.

2. Methods

2.1. Sample

The sample consisted of 9 healthy subjects (one woman), between 18 and 33 years old (22.9 ± 5 years old, mean $\pm$ SD). The anthropometric characteristics of the sample were: height, 174.9 ± 5 cm; body mass, 72.4 ± 9.2 kg; skeletal muscle mass, 33.9 ± 2.8 kg; body mass index, 23.3 ± 2.5 ; body fat percentage, 15.8 ± 6.8 %. Body composition was measured through bioimpedance testing (Inbody 230, Inbody, Seoul, Korea). Subjects were informed of the benefits and risks of the investigation prior to signing an informed consent. The study was approved by the Ethics Committee of the University of Granada and conform to the Declaration of Helsinki.

2.2. Procedures

2.2.1. General information

In order to analyse 3D posture, two Excel templates have been created: “DLT ALGORITHM-CAMERA CALIBRATION” and “DLT ALGORITHM-3D RECONSTRUCTION-POSTURAL ANALYSIS”. In the first, the four cameras are calibrated (the 11 DLT parameters are obtained) and in the second, the 3D position of the digitized markers is reconstructed and a series of postural parameters are calculated. Only the sheets of each template with tab in red and the cells with red borders must be modified by the users (Supplementary Figures 1 to 5). Excel templates can be downloaded from this link (the .ZIP file also includes some video tutorials): researchgate.net/profile/

2.2.2. Camera calibration template: DLT ALGORITHM-CAMERA CALIBRATION

Calibrating the cameras is necessary to reconstruct the position of the 3D markers and is equivalent to calculating the DLT parameters of each camera. There are different calibration algorithms. In this template the 11-parameter DLT algorithm is proposed, which should be used with cameras with little lens distortion [16]. These 11 calibration parameters are obtained by solving this system of equations, expressed in the form of matrices (Eq. 1).

$$\begin{array}{l}
 \text{Equation a point 1} \\
 \text{Equation b point 1} \\
 \text{Equation a point 2} \\
 \text{Equation b point 2} \\
 \vdots \\
 \text{Equation a point N} \\
 \text{Equation b point N}
 \end{array}
 \begin{bmatrix}
 x_1 & y_1 & z_1 & 1 & 0 & 0 & 0 & 0 & -u_{L1}x_1 & -u_{L1}y_1 & -u_{L1}z_1 \\
 0 & 0 & 0 & 0 & x_1 & y_1 & z_1 & 1 & -v_{L1}x_1 & -v_{L1}y_1 & -v_{L1}z_1 \\
 x_2 & y_2 & z_2 & 1 & 0 & 0 & 0 & 0 & -u_{L2}x_2 & -u_{L2}y_2 & -u_{L2}z_2 \\
 0 & 0 & 0 & 0 & x_1 & y_1 & z_1 & 1 & -v_{L2}x_2 & -v_{L2}y_2 & -v_{L2}z_2 \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 x_N & y_N & z_N & 1 & 0 & 0 & 0 & 0 & -u_{LN}x_N & -u_{LN}y_N & -u_{LN}z_N \\
 0 & 0 & 0 & 0 & x_N & y_N & z_N & 1 & -v_{LN}x_N & -v_{LN}y_N & -v_{LN}z_N
 \end{bmatrix}
 \begin{bmatrix}
 L_1 \\
 L_2 \\
 L_3 \\
 L_4 \\
 L_5 \\
 L_6 \\
 L_7 \\
 L_8 \\
 L_9 \\
 L_{10} \\
 L_{11}
 \end{bmatrix}
 =
 \begin{bmatrix}
 u_{L1} \\
 v_{L1} \\
 u_{L2} \\
 v_{L2} \\
 \vdots \\
 u_{LN} \\
 v_{LN}
 \end{bmatrix}
 \quad (1)$$

A minimum of 6 calibration points with known xyz values and pixel values (u_L and v_L) should be used to determine the 11 parameters mentioned. Equation (1) can be expressed as follows (the bold letters are used to refer to a matrix/vector) (Eq. 2).

$$\mathbf{F_L L} = \mathbf{g_L} \quad (2)$$

In equation (2), $\mathbf{L}$ would be the matrix of 11 rows and 1 column (contains the unknowns), $\mathbf{F}_L$ the matrix of 2N rows 11 columns and $\mathbf{g}_L$ the matrix of 2N rows and 1 column. This system of matrix equations is solved as Eq. 3 [17].

$$\mathbf{L} = (\mathbf{F}_L^T \mathbf{F}_L)^{-1} \mathbf{F}_L^T \mathbf{g}_L \quad (3)$$

where $\mathbf{F}_L^T$ is the transposed matrix of $\mathbf{F}_L$.

In the sheet “CALIBRATION POINTS” from the template “DLT ALGORITHM-CAMERA CALIBRATION” the coordinates in pixels of the calibration points digitized with an external software, such as Kinovea 9.3 (Kinovea.org, France), are pasted. Excel sheets 2 to 5 (“CAM CALIBRATION”) are used to calibrate each of the cameras using the 11-parameter DLT algorithm (all these sheets work in the same way, they are replicas). These sheets use the coordinates in metric units (the use of cm or mm is recommended) in columns C and E and in pixels (columns F and G) of the calibration points and return the 11 parameters of the DLT algorithm (column GJ) that will later be used to reconstruct the 3D coordinates of the markers in cm or mm. For further details about how the DLT algorithm works, read the classic paper of Challis and Kerwin [18], the original manuscript where the DLT algorithm was developed [10], or the paper on which the nomenclature of the formulas of the present manuscript is based [17]. This work is limited to the description of the Excel functions used.

The Excel formulas used to solve this matrix equation system appear in Table 1.

Table 1. Main Excel formulas used in the Excel template “DLT ALGORITHM-CAMERA CALIBRATION”

Sheet	Cells	Meaning	Source or formula
CALIBRATION POINTS	*O1	Metric length unit (cm, mm, m, inches, etc.)	Selected by the user
	*E3:G56	CP of the CF 1 in MLU	Actual measurements of the CF1
	*H3:S56	CP of the CF 1 in px on each camera	Digitizing the CF1 with specific software (e.g. Kinovea)
	*Y3:AA56	CP of the CF 2 in MLU	Actual measurements of the CF2
	*AB3:AI56	CP of the CF 2 in px on each camera	Digitizing the CF2 with specific software (e.g. Kinovea)
	*AO3:AQ56	CP of the CF 3 in MLU	Actual measurements of the CF3
	*AR3:AY56	CP of the CF 3 in px on each camera	Digitizing the CF3 with specific software (e.g. Kinovea)
CAM CALIBRATION	C5:E58	CP of the CF 1 in MLU	Cells E2:G55 from sheet “Calibration Points”
	F5:G58	CP of the CF 1 in px	Cells H2:O55 from sheet “Calibration Points”
	B5:B58	CP non visible of the CF 1	Columns H, K and N from sheet “Calibration Points”
	J5:U58	Equations A points 1 to N	See formula 1. Obtained from rank G5: G58
	X5:AI58	Equations B points 1 to N	See formula 1. Obtained from rank G5:G58
	AL5:AV112	F_L	Formed by joining equations A and B of CP
	AX5:AX112	g_L	Formed by joining constant of equations A and B of CP
	BA5:FD15	F_L^T	{=TRANSPOSE(AL5:AV112))}
	FG5:FQ15	$F_L^T F_L$	{=MMULT(BA5:FD15;AL5:AV112))}
	FT5:FT15	$F_L^T g_L$	{(=MMULT(BA5:FD15;AX5:AX112))}
CAM ERROR ADJUSTMENT	FW5:GG15	$(F_L^T F_L)^{-1}$	{=MINVERSE(FG5:FQ15)}
	GJ5:GJ15	L	{=MMULT(FW5:GG15;FT5:FT15)}
	A4:E57	CP of the CF 2 in px for the two cameras tested	Cells X2:AE55 from sheet “Calibration Points”
	DU2:DV12	DLT parameters from the two cameras tested	Cells GJ5:GJ15 from sheet “Cam Calibration”
	H4:DG57	3D reconstruction equations of the CP from the CF 2	See next section of the manuscript
	DI4:DK57	Computed 3D position of the CP from CF 2 in MLU	See next section of the manuscript
	DL4:DN57	Real 3D position of the CP from CF 2 in MLU	Cells U2:W55 from sheet “Calibration Points”
	DO4:DQ57	Absolute error in each axis	Range DI4:DK57 and range DL4:DN57
	DQ15	Mean Absolute Error for x axis CF 2 (unadjusted)	=AVERAGE(DO4:DO57)
	DR15	Mean Absolute Error for y axis CF 2 (unadjusted)	=AVERAGE(DP4:DP57)
	DS15	Mean Absolute Error for z axis CF 2 (unadjusted)	=AVERAGE(DQ4:DQ57)
	DQ19	Regression line slope to adjust the data (x-axis)	=SLOPE(DI4:DI57;DL4:DL57)
	DR19	Regression line slope to adjust the data (y-axis)	=SLOPE(DJ4:DJ57;DM4:DM57)
	DS19	Regression line slope to adjust the data (z-axis)	=SLOPE(DK4:DK57;DN4:DN57)
	DQ20	Regression line intercept to adjust the data (x-axis)	=INTERCEPT(DI4:DI57;DL4:DL57)
	DR20	Regression line intercept to adjust the data (y-axis)	=INTERCEPT(DJ4:DJ57;DM4:DM57)
	DS20	Regression line intercept to adjust the data (z-axis)	=INTERCEPT(DK4:DK57;DN4:DN57)
	DX4:EB57	CP of the CF 3 in px for the two cameras tested	Cells AN2:AU55 from sheet “Calibration Points”
	IX2:IY12	DLT parameters from the two cameras tested	Cells GJ5:GJ15 from sheet “Cam Calibration”
	EE4:ID57	3D reconstruction equations of the CP from the CF 3	See next section of the manuscript
	IF4:IH57	Computed 3D position of the CP from CF 3 in MLU	See next section of the manuscript
	II4:IK57	Adjusted 3D position of the CP from the CF 3 in MLU	Slope and intercept to adjust data (DQ19:DS20) and computed 3D position of CF 3 (IC4:IE57)
	IL4:IN57	Real 3D position of the CP from CF 3 in MLU	Cells AK2:AM55 from sheet “Calibration Points”
	IO4:IQ57	Absolute error in each axis (non-adjusted data)	Range IF4:IH57 and range IL4:IN57
	IR4:IT57	Absolute error in each axis (adjusted data)	Range II4:IK57 and range IL4:IN57
	IN15	Mean Absolute Error for x axis CF 3 (unadjusted)	=AVERAGE(IO4:IO57)
	IO15	Mean Absolute Error for y axis CF 3 (unadjusted)	=AVERAGE(IP4:IP57)
	IP15	Mean Absolute Error for z axis CF 3 (unadjusted)	=AVERAGE(IQ4:IQ57)
	IN18	Mean Absolute Error for x axis CF 3 (adjusted)	=AVERAGE(IR4:IR57)
	IO18	Mean Absolute Error for y axis CF 3 (adjusted)	=AVERAGE(IS4:IS57)
	IP18	Mean Absolute Error for z axis CF 3 (adjusted)	=AVERAGE(IT4:IT57)

CP: Calibration points; CF: Calibration Frame; px: pixels; MLU: Metric length unit

* The cells marked with an asterisk are those that must be modified by the user.

The "CAM ERROR ADJUSTMENT" sheet allows knowing the measurement error in cm or mm and correcting the error using the least square method. That is why the coordinates in pixels of three calibration frames should be obtained: the calibration frame to obtain the DLT parameters (calibration frame 1), the calibration frame to calculate the error and obtain the adjustment regression equation of the two cameras used to reconstruct a point (calibration frame 2) and the calibration frame to measure the measurement error in cm or mm, after adjustment using the calculated regression line (calibration frame 3). Calibration frame 1 is mandatory and calibration frames 2 and 3 are optional. Finally, the sheet "SUMMARY OF MEASUREMENT ERROR" collects the errors obtained for each camera pair, both from the adjusted and unadjusted data.

2.2.3. Marker 3D reconstruction template: DLT ALGORITHM-3D RECONSTRUCTION-POSTURAL ANALYSIS

To know the 3D coordinates in metric length unit of a point in space using two cameras, we must solve the system of equations expressed in matrix form (Eq. 4).

$$\begin{bmatrix} L_1 - L_9 u_L & L_2 - L_{10} u_L & L_3 - L_{11} u_L \\ L_5 - L_9 v_L & L_6 - L_{10} v_L & L_7 - L_{11} v_L \\ R_1 - R_9 u_R & R_2 - R_{10} u_R & R_3 - R_{11} u_R \\ R_5 - R_9 v_r & R_6 - R_{10} v_r & R_7 - R_{11} v_r \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} u_L - L_4 \\ v_L - L_8 \\ u_R - R_4 \\ v_R - R_8 \end{bmatrix} \quad (4)$$

This matrix equation contains the calibration parameters L_1-L_{11} (they are the DLT parameters of camera 1), R_1-R_{11} (DLT parameters of camera 2), u_L , v_L , u_R and v_R (coordinates in pixels in camera 1 and in camera 2 of the point we want to reconstruct). x , y and z are the unknowns of the system of equations and are the coordinates in metric length unit of the point we want to reconstruct.

It can be expressed as Eq. 5.

$$\mathbf{Q} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \mathbf{q}; \quad (5)$$

where $\mathbf{Q}$ is the 4 row and 3 column matrix and $\mathbf{q}$ is the 4 row and one column matrix. Eq. 5 is solved as Eq. 6 [17].

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = (\mathbf{Q}^T \mathbf{Q})^{-1} \mathbf{Q}^T \mathbf{q}$$

(6)

$(\mathbf{Q}^T \mathbf{Q})^{-1}$ is solved using the determinant calculation (Eq. 7).

$$(\mathbf{Q}^T \mathbf{Q})^{-1} = \frac{1}{|\mathbf{Q}^T \mathbf{Q}|} ((\mathbf{Q}^T \mathbf{Q})^*)^t$$

(7)

where $|\mathbf{Q}^T \mathbf{Q}|$ is the determinant of the matrix $\mathbf{Q}^T \mathbf{Q}$ and $(\mathbf{Q}^T \mathbf{Q})^*$ is the adjoint matrix of $\mathbf{Q}^T \mathbf{Q}$. To calculate the adjoint matrix we must replace each element with its adjoint one. Since $\mathbf{Q}^T \mathbf{Q}$ is a 3 x 3 matrix it will have a total of 9 adjoints.

The formulas to solve this system of equations are explained in Table 2 where only the reconstruction formulas of the first marker are shown (the reconstruction formulas of the rest of the markers are identical).

Table 2. Main Excel formulas used in the template “DLT ALGORITHM-3D RECONSTRUCTION-POSTURAL ANALYSIS”

Sheet	Cells*	Meaning	Source or formula
MARKER PIXELS COORDINATES	A1:P28	Coordinates in px* of the marker	External software (e.g. Kinovea)
	AC1:AV17	Mean Absolute Error and regression lines to adjust data	Calibration template
	AC20:AU20	The user indicates if he wants to use the adjusted data by writing a P	Depend on the magnitude of the error of the adjusted vs the unadjusted data (select the one with the minor value)
MARKER 3D RECONSTRUCTION	EC3:EF13	DLT calibration parameters	Calibration template
	A5:C66	Anatomical markers of the proposed model	Model (based on bibliography)
	D5:G66	Cameras used to reconstruct each marker	Depending on the camera set
	H5:O66	Coordinates in px of the anatomical markers	Sheet “Marker pixels coordinates”
	P5:P66	The letters refer to the pair of cameras that see the marker (see range T1:W3).	Depends on the cameras that better see each anatomical marker.
	Q5:AB5*	Q	DLT parameters and coordinates in px
	AC5:AF5*	q	DLT parameters and coordinates in px
	AG5:AR5	Q^T	Cells Q4:AB4
	AS5:BA5	$Q^T Q$	Cells Q4:AB4 and range AG4:AR4
	BB5:CK5	9 adjoints from matrix $Q^T Q$	Range AS4:BA4
	CL5:CT5	$(Q^T Q)^*$	Range BB4:CK4
	CU5	$1/ Q^T Q $	Range AS4:BA4
	CV5:DD5	$((Q^T Q)^*)^t$	Range CL4:CT4
	DE5:DM5	$(Q^T Q)^{-1}$	Range CV4:DD4
	DN5:DP5	$Q^T q$	Range AC4:AR4
	DY15:EB29	Regression lines slope and intercept to adjust data	Calibration template
	DR5:DT5	xyz coordinates in MLU (unadjusted)*	Range DE4:DP4
	DU5:DW5	xyz coordinates in MLU adjusted*	Range DR4:DT4 y range DY15:EB29
	DX5:DZ5	xyz coordinates in MLU selected	Range DR5:DW5 and range AC20:AU20 from sheet “MARKER PIXELS COORDINATES”

*Px: Pixels; *MLU: Metric length unit

* Q y q change according to the pair of cameras used to reconstruct the markers

Users first has to link the 3D reconstruction Excel sheet (DLT ALGORITHM-3D RECONSTRUCTION-POSTURAL ANALYSIS) with the calibration sheet (DLT ALGORITHM-CAMERA CALIBRATION). In this way, multiple 3D reconstruction sheets can share the same calibration sheet. This is done in “Connections”, in the Excel tab “Data”. There the user has to click on the “Edit Links” option where he will select the calibration Excel template.

The following sheet ("MODEL PROJECTIONS") shows the orthonormal projection of the markers on the transverse (xy), sagittal (yz) and frontal (xz) planes. It is a way of visually checking that the analysis is correct. In the sheet “POSTUROGRAPHIC MEASUREMENTS-2D”, a series of anthropometric parameters appear based on a previous manuscript [19]. Projections of the markers were used in the transverse, sagittal and frontal planes. Distances are calculated using the Pythagorean theorem. 2D angles were calculated based on the scalar product of two vectors. The last sheet "POSTUROGRAPHIC REPORT" can be printed in PDF for the patient.

Let's look at an example of calculating a distance: the distance between glabella (with the spatial coordinates G_x, G_y, G_z) and the chin (with the spatial coordinates M_x, M_y, M_z), shown in cell D8. We calculate the components **ay** and **az** of the vector **a** which is the projection on the yz-plane of the vector that goes from the glabella to the chin (since it is a projection on said plane **ax** is of magnitude 0) (Eq. 8).

$$ay = Gy - My; az = Gz - Mz; \quad (8)$$

In the Excel sheet these components are calculated with the following formulas (cell B8 and C8):

= 'MARKERS 3D RECONSTRUCTION'!DR44-'MARKERS 3D RECONSTRUCTION'!DR45

= 'MARKERS 3D RECONSTRUCTION'!DS44-'MARKERS 3D RECONSTRUCTION'!DS45

Once the components are known, we calculate the magnitude of vector **a**, which is the distance we want to know (Eq. 9).

$$|a| = \sqrt{ay^2 + az^2} \quad (9)$$

In Excel it is calculated with the formula (cell D8):

$$=SQRT(A8^2+B8^2+C8^2)$$

For the calculation of angles, we rely on the formulas of the scalar product of two vectors. For example, the rearfoot angle (cell L265) is calculated with the calcaneus (C), Achilles tendon (A) and gastrocnemius (G). We calculate the components yz of the vector that joins the Achilles tendon and the calcaneus (**e**) and of the vector that joins the Achilles tendon and the gastrocnemius (**f**) (component x will be 0 since we are using the projection) (Eq. 10).

$$ey = Cy - Ay; ez = Cz - Az; fy = Cy - Ay; fz = Cz - Az \quad (10)$$

They are solved in excel cells B265, C265, E265, F265 with the formulas:

$$='MARKERS\ 3D\ RECONSTRUCTION'!DY66-'MARKERS\ 3D\ RECONSTRUCTION'!D26$$

$$='MARKERS\ 3D\ RECONSTRUCTION'!DZ66-'MARKERS\ 3D\ RECONSTRUCTION'!DZ26$$

$$='MARKERS\ 3D\ RECONSTRUCTION'!DY25-'MARKERS\ 3D\ RECONSTRUCTION'!DY26$$

$$='MARKERS\ 3D\ RECONSTRUCTION'!DZ25-'MARKERS\ 3D\ RECONSTRUCTION'!DZ26$$

We calculate the scalar product of vectors **e** and **f** as Eq. 11.

$$e \cdot f = |ex| \cdot |fx| + |ey| \cdot |fy| + |ez| \cdot |fz| \quad (11)$$

In Excel it is solved in cell G265 with the formula:

$$=A265*D265+B265*E265+C265*F265$$

We calculate the modulus of the component of each vector as Eq. 12.

$$|e| = \sqrt{ey^2 + ez^2} ; |f| = \sqrt{fy^2 + fz^2} \quad (12)$$

In Excel they are solved in cells H265 and I265 with the formulas:

$$=\text{SQRT}(A265^2+B265^2+C265^2); =\text{SQRT}(D265^2+E265^2+F265^2)$$

Knowing the scalar product of two vectors and the modulus of each vector, we obtain the cosine of the angle α (the arccosine will be the angle α) (Eq. 13).

$$\mathbf{e} \cdot \mathbf{f} = |\mathbf{e}| \cdot |\mathbf{f}| \cdot \cos \alpha; \cos \alpha = \frac{\mathbf{e} \cdot \mathbf{f}}{|\mathbf{e}| \cdot |\mathbf{f}|}; \alpha = \cos^{-1} \left(\frac{\mathbf{e} \cdot \mathbf{f}}{|\mathbf{e}| \cdot |\mathbf{f}|} \right) \quad (13)$$

In Excel they are solved in cells J265, K265 and L265 with the formulas:

$$=G265/(H265*I265); =\text{ACOS}(J265); =\text{DEGREES}(K265)$$

Complementary and supplementary angles are shown in cells M265 and N265 (they may have an anatomical meaning that is easier to understand).

The marker set implemented in the Excel template and the anthropometric variables measured are shown in Figure 1.

<ul style="list-style-type: none"> • Calcaneus (1 y 15) • Achilles tendon (2 y 16) • 2nd-3rd metatarsus (3 y 17) • Medial malleolus (4 y 18) • Lateral malleolus (5 y 19) • Lateral condyle (6 y 20) • Tibial Tuberosity (7 y 21) • Centre of the patella (8 y 22) • Trochanter (9 y 23) • ASIS (10 y 24) • Acromion (11 y 25) • Lateral epicondyle (12 y 26) • Radioulnar joint (13 y 27) • Earlobe (14 y 28) • Glabella (29) • Chin (30) • C7 (31) • T1 (32) • T3 (33) • T11 (34) • L1 (35) • L4 (36) • S2 (37) • Scapula's inferior angle (38 y 39) • Intersection of the scapula spine (40 y 41) • PSIS (42 y 43) • Gastrocnemius (44 y 45)

Parameters computed in the Excel template. The points that form the vector required to calculate the parameter are in parentheses ("hor." refers to a vector on the horizontal, parallel to the x- [sagittal view] or y-axis [frontal and posterior view])		
Frontal view	Sagittal view*	Posterior view
<ul style="list-style-type: none"> • Glabella-chin distance (29-30) • Interacromial length (11-25) • Inter ASIS distance (10-24) • Right femur length (9-6) • Right tibia length (5-6) • Leg length difference (10-4 and 24-18) • Inclination of the head (29-30 and hor.) • Hor. align. of head (14-28 and hor.) • Hor. align. of acromions (11-25 and hor.) • Hor. align. of ASIS (10-24 and hor.) • Anterior align. of the right lower limb (6-9 and 5-6) • Q angle of right lower limb (8-10 and 7-8) • Angle acromions-ASIS (11-24 and 10-24) • Horizontal alignment of the lateral condyles (6-20 and hor.) 	<ul style="list-style-type: none"> • Hor. align. of head (C7) (14-31 and hor.) • Hor. align. of the head (acromion) (11-14 and hor.) • Horizontal alignment of the pelvis (10-42 and hor.) • Sagittal align. of the lower limb (5-6 and 6-9) • Angle of the hip joint (6-9 and 9-10) • Angle of the ankle (5-6 and hor.) • Ver. align. of the torso (9-11 and hor.) • Ver. align. of the body (5-11 and hor.) • Sagittal align. of the body (5-9 and 9-11) • Angle of the thoracic kyphosis (32-33 and 34-35) • Lumbar Lordosis Angle (LLA) (34-35 and 36-37) 	<ul style="list-style-type: none"> • Distance between scapula's inferior angle and intersection of the scapula spine (38-40) • Distance between scapula's inferiors borders (38-39) • Distance between gastrocnemius and Achilles (right) (2-44) • Inter PSIS distance (42-43) • Align. of the scapulas related to T3 (33-40 and 33-41) • Scapular align. (right) (38-40 and hor.) • Rearfoot angle (1-2 and 2-44)

Figure 1. Marker set and list of variables computed by the Excel spreadsheet. Hor.: Horizontal; Ver.: Vertical; Align.: Alignment. For simplicity and ease of understanding, only the parameters of the right half of the body are shown.

2.2.4. Practical considerations 1: camera placement and synchronization

The Excel is designed to use 4 cameras, positioned around the subject to be evaluated, forming a rectangle. The distribution of the cameras in this study is shown in Figure 2. The view from each camera is shown in figure 3. The way the cameras are distributed is important since the precision of the DLT algorithm depends among other factors on the angle between the optical axes of the two cameras [20]. When this angle is too small or too large, the accuracy of the 3D reconstruction is greatly diminished, and the estimated parameters are largely imprecise. An angle between 30 and 150 degrees is recommended [20].

In the Excel sheet the cameras are named as follows (relative to the subject being analysed): number one is in front and on the right, two in front and on the left, three behind and on the right and four behind and on the left (Figure 2). The distance from the camera to the subject being assessed must be sufficient to bring the entire silhouette of the subject into the camera's field of view, which will depend largely on the focal length. It is therefore possible to use the method in smaller spaces than shown in Figure 2. In this work 4 mvBluecougar-XD104C cameras (Matrix Vision GmbH, Oppenweiler, Germany) were used, with a resolution of 2048 x 1088 pixels. The cameras were synchronized with each other using a Cisco SG500X-24-K9 switch (San Jose, USA) and a National Instruments (Texas, USA) USB-6225 analogy digital converter. The SIMI software was used to make the recording of the video. The sampling frequency was fixed to 50 frames per second and light-emitting diode (LED) ring-lights were mounted on the cameras. In case the user does not have a hardware synchronisation device, a visual (e.g. impact of a ball on the floor) or sound (using a clapperboard) event could be used. To prevent the cameras from moving after the calibration process we recommend the use of a trigger external to the camera.

Figure 2. Set-up of the two camera systems employed in the experiment (MV: Matrix Vision cameras; QL: Qualisys cameras; O: Coordinates origin). Camera position relative to O in cm and average residuals (avg. res.) in mm are: QL1 ($x = 371$; $y = -218$; $z = 239$; avg. res. = 0.98); QL2 ($x = 320$; $y = 31$; $z = 108$; avg. res. = 0.82); QL3 ($x = 395$; $y = 10$; $z = 241$; avg. res. = 0.69); QL4 ($x = 396$; $y = 365$; $z = 230$; avg. res. = 0.88); QL5 ($x = -489$; $y = -181$; $z = 243$; avg. res. = 0.9); QL6 ($x = -151$; $y = -238$; $z = 241$; avg. res. = 0.89); QL7 ($x = -539$; $y = 107$; $z = 263$; avg. res. = 1.01); QL8 ($x = -204$; $y = 324$; $z = 278$; avg. res. = 0.73); QL9 ($x = 102$; $y = 466$; $z = 287$; avg. res. = 1.03); MV1 ($x = 401$; $y = -178$; $z = 241$); MV2 ($x = 378$; $y = 204$; $z = 191$); MV3 ($x = -182$; $y = -216$; $z = 231$); MV4 ($x = -203$; $y = 194$; $z = 274$). Focal length of Qualisys cameras was of 17 mm (except for camera 3 and 5, where it was 25 mm) and for the MVBlue cameras was of 12.5 mm.

2.2.5. Practical considerations 2: recording and digitizing the calibration video

Calibration is done using a vertical pole with marks at known heights. For this work we have used an extendable tripod with six marks at 30, 65, 88.5, 110.5, 140 and 189 cm height from the ground. A recording must be made in which the pole is placed on top of a series of dots drawn on the ground with coordinates in metric length unit, also known. Round stickers have been used in this work forming a rectangle of 80 x 50 cm. This creates a virtual calibration frame (Figure 3a). This method is similar to that proposed in a previous manuscript [15]. It is a quick way to calibrate and avoids having to use a bulky calibration frame, which many laboratories cannot afford due to lack of space. It also allows obtaining a large number of calibration points. The excel is designed so that the x-axis goes in the mediolateral direction of the subject to be measured (from its right to left half), the y-axis in the posteroanterior direction and the z-axis in the vertical direction (positive upward direction). The sheet accepts up to 54 calibration points (cf. [21]).

If the user wants to obtain the error of the measurement in metric length unit, a second recording must be made, to obtain the calibration points of calibration frame 2 because to evaluate the error, it is more appropriate to use a different calibration volume to the one used to get the camera's DLT parameters. In that way the measurement are independents and reflect the accuracy of the technique in locating unknown points in space, and not only the mathematical techniques employed [18]. Said calibration volume also allows obtaining the slope and the ordinate at the origin of a regression line that allows adjusting the position of the markers in space. If the users want to know the error of the adjusted values, it is necessary to record and digitize calibration frame 3 with different calibration points than calibration frame 1 and calibration frame 2.

2.2.6. Practical considerations 3: recording and digitization of the subject to be analysed

The Excel sheet includes the marker model shown in Figures 1 and 3. Reflective markers of 6 and 12 mm have been used in this work because it is intended to compare the results with those of a 3D OMC system based on infrared cameras, but in another case, it is possible to use a skin-marker pencil. The recording was made with the heels above a marked line on the ground and

with the elbows at 90 degrees so as not to occlude the markers of the trochanters with the hands. To study inter-recording reliability, two videos per subject were recorded (Figure 4). After recording number one, the subject was asked to lower their arms and relax, and then the following recording was made. The user can analyse a video to consider the postural sway or a photo to simplify the process.

To do the digitization, the authors recommend using an image analysis software that allows to save a "model" file and that have a zoom that allows to place the marker accurately. In this work, Kinovea was used, which allows saving the model in a file with Kinovea video analysis (KVA) extension, which must have the same name as the video to be analysed. It is not mandatory to digitize all the markers. The Excel sheet can for example be used to reconstruct only the markers located on the spine, using only the two posterior cameras.

Each evaluator digitized recording number one twice, in order to calculate the intra-rater reliability. Recording number two was only digitized once for each evaluator. Comparing the first digitization of recording one with that of recording two of the same evaluator, the inter-recording reliability was evaluated (Figure 4).

In order to have a measure of the time required to perform the digitization of the marker the time of six digitizations was measured with a manual stopwatch (Casio HS-80TW-1EF, Tokio, Japan).

Figure 3. View of each of the cameras in this research. Example of a virtual calibration frame (Figure 3a) and markers that are digitized on each camera (Figure 3b, Figure 3c and Figure 3d).

2.2.7. Comparative study of the system shown and a photogrammetric system (Qualisys) with submillimetre accuracy

The difference was calculated with Qualisys (Qualisys Motion Capture Systems, Gothenburg, Sweden) a 3D OMC system based on infrared cameras (in the present study we used 8 Oqus-4 cameras) that shows submillimetre accuracy [22]. The camera arrangement is shown in Figure 2. To synchronize Qualisys and mvBluecougar-XD104C cameras a visible event on both was used: the bounce of a reflective marker on the ground. The frame number 20 after this event was considered on both systems for the digitization of the anatomical model (it corresponded to the same instant of time since both systems recorded at 50 frames per second).

Once the coordinates were obtained in Qualisys, they were saved in a Coordinate 3D (C3D) file extension and the markers were labelled using the software Mokka Biomechanics (Biomechanical ToolKit, Lausanne, Switzerland). The 3D position of the markers was used to obtain the same postural variables as with the postural analysis Excel template (we selected a series of parameters trying to take measurement in the horizontal and vertical direction): head horizontal alignment, horizontal alignment of the acromions, horizontal alignment of the anterior superior iliac spines, angle between the two acromions and the two anterior superior iliac spines, frontal angle of the right and left lower limb, horizontal alignment of tibial tuberosities, right Q angle, rearfoot angle (right and left). The following distances were also calculated: distance between earlobes, distance between acromions, distance between ASIS, distance between medial malleolis, right and left femur length, right and left tibia length, distance between the scapula's inferior angles, gastrocnemius-Achilles distance (right and left).

2.3. Statistical analysis

Data treatment was done with Real Statistic Using Excel Packages [23]. The values obtained by using Qualisys were compared with that obtained by using the Excel templates based on the following statistical parameters: Root Mean Square Error (*RMSE*), Mean Absolute Error (*MAE*), Pearson's *r*, Lin's concordance correlation coefficient (Lin's CCC) and Bland-Altman Plot (BA Plot). The linear relationship and level of agreement were evaluated with the Pearson's

r and Lin's CCC, with a high CCC indicating the absence of systematic error difference between measurements [24]. To evaluate the strength of agreement for correlation coefficients the following scale was used [25]: > 0.99 almost perfect, $0.95-0.99$ substantial, $0.90-0.95$ moderate, and < 0.90 poor. We also graph the Bland–Altman plots, to check residuals homoscedasticity [26,27]. The differences between Qualisys and the Excel Spreadsheet were evaluated with the *RMSE* and the *MAE*. The *RMSE* was included because it allows to express the variability of the differences [26] in the same unit of the measuring system. Although the *RMSE* is more popular in this type of researches we also include the *MAE* (based on the absolute difference between both measures) as there are certain authors who defend that its use is more correct because the *RMSE* varies with the variability within the distribution of differences magnitudes and with the square root of the number of differences [28].

In addition to the comparison between the two systems, inter-rater reliability (comparing each evaluator's first digitization of recording number one), intra-rater reliability and inter-recording reliability were measured (subsection 2.2.6 and Figure 4). For this, the *RMSE*, *MAE*, BA plot, Lin's CCC and Pearson's r were used. Qualisys inter-recording reliability was also calculated.

Figure 4. Flow diagram including the comparisons made in the present work to study the validity and reliability of the proposed method.

Outliers were removed using the median and the median absolute deviation (*MAD*). This method is preferable to use the mean and the standard deviation, as outliers are not sensitive to median and *MAD* [29]. These authors advise the use of a value of 3 times the *MAD*, but in this work a conservative value of 3.5 times the *MAD* was used.

3. Results

The methodology showed errors (*RMSE*) in both evaluators of between 1 and 2 degrees for the angles and about 2 mm for the distances (Table 3). In the case of inter-evaluator and inter-recording reliability the *RMSE* values were between 1.25 and 1.85 degrees and very close to the millimetre (Table 3).

Table 3. Measures of validity and reliability of the proposed methodology

Analysis	Variable	Evaluator 1		Evaluator 2	
		Angle	Distance	Angle	Distance
Comparison with Qualisys	<i>n</i>	85	93	81	93
	Mean	0.02	-0.09	0.14	-0.07
	<i>SD</i>	1.18	0.43	0.95	0.45
	<i>MAE</i>	0.90	0.36	0.74	0.40
	<i>RMSE</i>	1.38	0.19	0.92	0.20
Intra-evaluator reliability (Excel)	<i>n</i>	85	86	90	91
	Mean	0.22	0.01	0.04	-0.01
	<i>SD</i>	1.35	0.33	1.22	0.23
	<i>MAE</i>	1.02	0.26	0.95	0.18
	<i>RMSE</i>	1.85	0.11	1.48	0.05
Inter-recording reliability (Excel)	<i>n</i>	85	86	79	85
	Mean	0.16	-0.02	-0.07	-0.03
	<i>SD</i>	1.12	0.31	1.21	0.30
	<i>MAE</i>	0.86	0.23	0.91	0.24
	<i>RMSE</i>	1.25	0.09	1.45	0.09

* The Lin CCC and the Pearson *r* were in all cases greater than 0.999

* In total, 99 distance data and 99 angulation data were obtained

* Values are in degrees (for the angle) and in cm (for the distance)

The BA plots of the comparisons between Qualisys and the results of the Excel spreadsheet showed heterogeneity in the residuals (Figure 5). The BA plots of the reliability measures showed heterogeneity in the residuals and the r^2 were less than 0.02 in all cases except in two that it was less than 0.04 (inter-recording reliability for the angle of evaluator 1 and inter-recording reliability for the distance of evaluator 2).

In Qualisys, comparing the data from the first measurement with the data from the second measurement (inter-recording reliability) 85 values for the distance and 93 values for the angle were analysed. The Lin's CCC was of 0.976 for the angle and 0.995 for the distance; the *RMSE* was of 1.39 degrees and 0.20 cm; the *MAE* was of 0.90 degrees and 0.37 cm and the mean and *SD* of the error were of 0.02 ± 1.18 degrees ($n = 85$) and -0.11 ± 0.44 cm ($n = 93$). The residuals in the BA plot showed heterogeneity (the r^2 of the residuals were of 0.024 and of 0.034 for the angle and for the distance respectively).

Regarding the inter-evaluator reliability, the number of values analysed for the angle was 84 and 89 for the distance. The Lin's CCC and the Pearson's r were greater than 0.999 in both cases. The *MAE* for the angle was 0.82 degrees and 0.18 cm for the distance. The *RMSE* was 1.18 degrees and 0.05 cm. The mean of the difference was of -0.27 ± 1.06 degrees and of -0.04 ± 0.23 cm.

Figure 5. Bland Altman Plots of angles (a and c) and distances (b and d) of evaluator 1 (a and b) and evaluator 2 (c and d). Dash dot line: regression line. Round dot line: $DE \pm 2 SE$; Long dash line: Mean $\pm 2 DE$; Square dot line: Mean.

Finally, the average time to digitize a complete model in the four cameras and computing the anthropometric parameters was 13 ± 3 min, not including the time of the calibration (since the same calibration can be used as long as the cameras do not move).

4. Discussion

This work shows a 3D postural analysis tool, based on the DLT algorithm, simple to use, portable and affordable for any healthcare professional. Since this algorithm has been widely used and the sources of error have been studied in detail, the method showed good accuracy, as expected. The error, measured as *RMSE*, compared to a 3D OMC system based on infrared cameras was less than 1.5 degrees for angle measurements and approximately 2 mm for distance measurements. The differences in the BA plots showed heterogeneity. A high reliability was also found intra-evaluator, inter-recording and inter-evaluator, with the *RMSE* values being between 1 and 2 degrees for the angles, close to 1 mm for the distance and the Lin's CCC greater than 0.99. The BA plots, in this case, also showed heterogeneity in the residuals. The main contribution of this work is the development of the Excel calibration templates and the reconstruction/obtaining of postural parameters. We did not want to focus on the hardware to be used or on the layout of the cameras, taking into account that that camera configurations of laboratories or clinics can differ considerably (quality of the cameras, size of the laboratory, layout of the furniture, etc.). Since the Excel sheet allows the error to be calculated in real units, the best thing is for each researcher/healthcare professional to evaluate the accuracy of each data collection and thus make decisions on whether the data is suitable for their objectives.

Regarding the magnitude of the error, our data agrees with that of other works that use the DLT algorithm. For example, in a study by Challis and Kerwin [18] in which the accuracy of this algorithm is analysed using different types of calibration volumes, *RMSE* of between 2 and 3 mm were obtained. In another study [30] in which a known photogrammetric system (APAS Ariel) was used, very small errors were reached (*RMSE* below 0.5 mm in all cases) but these authors calibrate a smaller volume than that of this work (a cube 30 cm in

diameter) and when the calibrated space is large, there is reduction in the size of the image relative to the calibrated volume which increases the 3-D reconstruction error [31]. In fact this same system (APAS Ariel), which also uses the DLT algorithm, showed errors of between 1 and 5 mm when higher calibration volumes were used (1 x 1 x 1 m and 1 x 3 x 1 m) [31]. Using a similar volume (1,875 m cubed calibration frame) in a study of the golf swing [32], *RMSE* of 5.1 to 9.8 mm were reported. Regarding the reliability of the data, the differences were very low. This makes the proposed methodology very suitable for studies of repeated measures, where the reliability of the apparatus may be more important than its accuracy.

From the results of the previous studies we can deduce that there is a great variability in the error, even between different studies that use the same software. This variability is due to the fact that for the 3D camera calibration and marker reconstruction there are various sources of error such as the algorithm used [16], the resolution of the cameras [33], the type of calibration frame used [18], the number of cameras used to reconstruct the 3D position and the angle between the cameras [34] or the camera lens distortion [35]. It is complex to determine if the error found is large or small, since that will depend on the purposes of each study. Let's put two real examples: one for which it could be used and another for which it could not. A discrepancy between both legs of between 6 and 11 mm affects gait [36]. Our System is sensitive enough to capture that difference, so it can be used in that case. On the other hand, if what is intended is to study facial asymmetries, systems with submillimetre accuracy are required [37–39] and the methodology shown here should not be used. Harrison et al. [40] hypothesized that horizontal and vertical translation measurements with an error (bias) of less than 5 mm and rotations with a bias of less than 5 degrees are acceptable for clinical use. This criterion is appropriate when comparing a measured body position to a known position of a mannequin as done by Harrison et al. [40] but the range of acceptable values may be greater when studying humans who normally have some degree of sway in the standing position [41].

The methodology proposed here does not have a problem of occlusion of markers as it can happen with some 2D softwares. For example, Ferreira et al.

[19] have to use groups of 3 polystyrene spheres superimposed on each vertebra to provide visualization on lateral views. Another advantages of this methodology are: 1) it allows evaluating both a photo and a video having into account the postural sway (taking advantage of automatic tracking by Kinovea or other softwares); 2) calibration file can be imported, so if the cameras do not move, the same calibration file could be used in different occasions; 3) it allows knowing the measurement error using a second calibration volume, independent of the one used to obtain the DLT calibration parameters. Its main limitation is that it implements the 11-parameter DLT algorithm and it is recommended to use cameras that do not have lens distortion. An option that could perhaps work to minimize the error in cameras with evident lens distortion is to correct it before doing the digitization. Kinovea 9.3 for example includes an utility that allows to do it, using other free software: Agisoft Lens (Agisoft LCC, Russia) [42]. It would be a similar process to that proposed by Rossi et al. [35] which states that the lens distortion correction previous to the calculation of the DLT implicit parameters and the 3D markers reconstruction reduces the systematic errors substantially. Future studies should also assess the magnitude of the error using the least squares-based adjustment method, implemented in the Excel calibration template. Another limitation of the proposed methodology is the need for manual digitization of the markers, unlike when using a 3D OMC system based on infrared cameras. This could be positive in case the lighting conditions in the room are not ideal (surface reflections can be confused with reflective markers when using automatic systems) and even allows the location of anatomical points without the use of physical markers. In addition, models using skin based markers are prone to systematic errors [43].

5. Conclusions

To our knowledge this is the first time Excel templates have been introduced that implement the DLT algorithm, and that automatically calculate a series of anthropometric parameters. The methodology shown here can be used with any type of commercial camera. Calibration and analysis do not require

mathematical knowledge so we think it can be used for both research and clinical use. The errors were of about 2 mm and between 1 and 2 degrees, which is acceptable in most cases. It also shows high reliability which makes it especially useful in studies of repeated measurements.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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[SUPPLEMENTARY FIGURES NOT PROVIDED WITH THIS VERSION OF THE MANUSCRIPT. For access, please contact the authors]

Supplementary figure 1. Modifiable fields of the sheet “CALIBRATION POINTS” from the template “DLT ALGORITHM-CAMERA CALIBRATION” related with calibration frame 1.

Supplementary figure 2. Modifiable fields of the sheet “CALIBRATION POINTS” from the template “DLT ALGORITHM-CAMERA CALIBRATION” related with calibration frame 2.

Supplementary figure 3. Modifiable fields of the sheet CALIBRATION POINTS from the template “DLT ALGORITHM-CAMERA CALIBRATION” related with calibration frame 3.

Supplementary figure 4. Modifiable fields of the sheet “MARKER PIXELS COORDINATES” from the template “DLT ALGORITHM-3D RECONSTRUCTION-POSTURAL ANALYSIS” (related with the anatomical model)

Supplementary figure 5. Modifiable fields of the sheet “MARKER PIXELS COORDINATES” from the template “DLT ALGORITHM-3D RECONSTRUCTION-POSTURAL ANALYSIS” (to select adjusted or unadjusted data).