New equations to calculate 3D joint centres in the lower extremities

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ABSTRACT

Biomechanical movement analysis in 3D requires estimation of joint centres in the lower extremities and this estimation is based on extrapolation from markers placed on anatomical landmarks. The purpose of the present study was to quantify the accuracy of three established set of equations and provide new improved equations to predict the joint centre locations. The 'true' joint centres of the knee and ankle joint were obtained in vivo by MRI scans on 10 male subjects whereas the 'true' hip joint centre was obtained in 10 male and 10 female cadavers by CT scans.

For the hip joint the errors ranged from 26.7 (8.9) to 29.6 (7.5) mm, for the knee joint 5.8 (3.1) to 22.6 (3.3) mm and for the ankle joint 14.4 (2.2) to 27.0 (4.6) mm. This differed significantly from the improved equations by which the error for the hip joint ranged from 8.2 (3.6) to 11.6 (5.6) mm, for the knee joint from 2.9 (2.1) to 4.7 (2.5) mm and for the ankle joint from 3.4 (1.3) to 4.1 (2.0) mm. The coefficients in the new hip joint equations differed significantly between sexes. This difference depends on anatomical differences of the male and female pelvis.

1. Introduction

Movement analyses of the lower extremities in three dimensions are typically based on motion capture of markers placed on anatomical landmarks according to a marker setup by which the anatomical hip, knee and ankle joint centres are predicted by regression equations. However, the usage of markers has several kinematic and kinetic limitations due to soft tissue artefacts (STA) and variations in the marker placement [1-7]. Besides STA and variability of the marker placement, errors associated with the regression equations used to calculate the joint centre locations are also considerable [8–10]. The regression equations are either based on functional methods or predictive methods. Functional methods estimate the centre of rotation of a rigid motion between two segments through optimisation [11], but in many patient groups functional calibration has been reported to be difficult [10]. Most biomechanical analysis systems use regression equations based on predictive methods to calculate joint centres. Kadaba et al. [12], Davis et al. [13] and Vaughan et al. [14] (Vaughan I)

provided detailed descriptions of a marker based systems to calculate joint centres in the lower extremities. The marker setup used by Davis et al. [13], Kadaba et al. [12] and Vaughan et al. [15] (Vaughan II) is commonly referred to as Helen Hayes Hospital marker setup and the regression equations are referred to as the Plug-in gait model, VICON Clinical Manager or the Conventional Gait Model (CGM). In this study, these equations are referred to as CGM.

The first marker setup by Vaughan I was based on 15 markers attached directly on the skin. The joint centre regression equations were estimated from a single subject ($N = 1$), which implies some bias. In 1999, Vaughan II adopted the marker setup in the CGM to improve the limitations of estimating the internal/external rotations as this marker set had a higher sensitivity by using wand markers. However, accurate placement of the wands is difficult and they suffer from vibrations [7]. The original marker setup by Vaughan I is therefore still being used. The regression equations by Vaughan II were based on 12 male subjects but the errors of the joint centre predictions were omitted. The regression equations in the CGM are based on the HJC regression equation by Davis et al. [13] and *chord functions* to predict the knee and the ankle joint centres [16]. The HJC regression equation was based on 25 male subjects and has been validated in later studies [8–10] showing significant errors, which were corrected with new regression equations. The chord functions predict the knee joint

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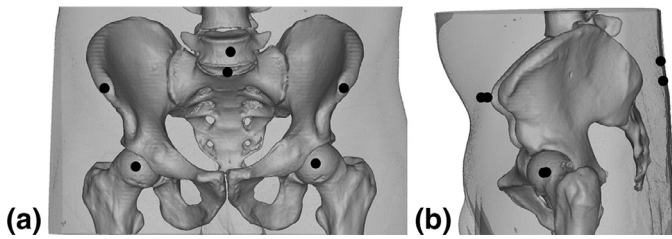E-mail address: msc@dbi-net.dk (M. Sandau).

Fig. 1. 3D reconstruction of a CT scan. The black dots are the labelled anatomical landmarks. (a) Coronal view. (b) Sagittal view.

centre (KJC) and the ankle joint centre (AJC) with the assumption that the joint centres are lying on the transepicondylar axis and the transmalleolar axis in the frontal plane, respectively. This assumption seems reasonable for the knee [17, 18], but to a lesser extent regarding the ankle joint [19]. Moreover, the actual prediction errors for both the KJC and the AJC have not been published.

Previously, sex differences in HJC regression equations have only been studied by Seidel et al. [20] but these results referred to a different predictive method and surprisingly the results showed no differences between sexes.

The purpose of the present study was (1) to quantify the errors of the regression equations by Vaughan I, Vaughan II and the CGM and provide new equations to predict the HJC, the KJC and the AJC and (2) to provide new equations to calculate the HJC with respect to differences between the sexes.

2. Methods

2.1. Subjects

The HJC regression equations were based on CT scans of 10 male and 10 female cadavers. All subjects were Caucasians in the age between 21 and 57 years with a *body mass index* (BMI) between 17.8–27.2 kg/m^2. The CT scans were performed using a Somatom Definition CT scanner (Siemens AG, Erlangen, Germany) with the following settings: 120 kV and 285 mAs and a spatial resolution at $3 \times 3 \times 3$ mm^3/voxel.

For the KJC and AJC regression equations, MRI scans of 10 male subjects were included. The height of the subjects ranged between 1.78 and 1.89 m and they had a BMI between 20.6 and 25.7 kg/m^2. Structural MRI scans were obtained with a 1.0 Tesla, Harmony MRI scanner (Siemens AG, Erlangen, Germany) with a spatial resolution of $0.8 \times 0.8 \times 3.0$ mm^3/voxel. The low resolution was orthogonal to the frontal plane. The Transmit-receiver body coil was used for excitation and signal detection. A gradient echo T$_1$-weighted pulse sequence was used in order to provide the best possible tissue contrast between muscle and bone tissue.

MRI scans of living adults were preferred to analyse the KJC and the AJC, as CT scans in such circumstances would be unacceptable according to the Danish Ethical Committee. However, to analyse the HJC, CT scans (on cadavers) were preferred because CT provides excellent images of the bone and respiration induced motion artefacts were avoided by using cadavers.

The anatomical landmarks used to position markers in the different marker setups and the anthropometric measurements were extracted directly from the scans in MIMICS (Materialise, Leuven, Belgium) and MATLAB (Math Works Inc., MA, USA) as illustrated in Fig. 1. The leg length of the subjects was measured from the anterior superior iliac spine (ASIS) to the medial malleolus.

2.2. Regression equations by Vaughan I

Segment **uvw**-reference frames were defined by the anatomical landmarks in accordance with Vaughan I as illustrated in
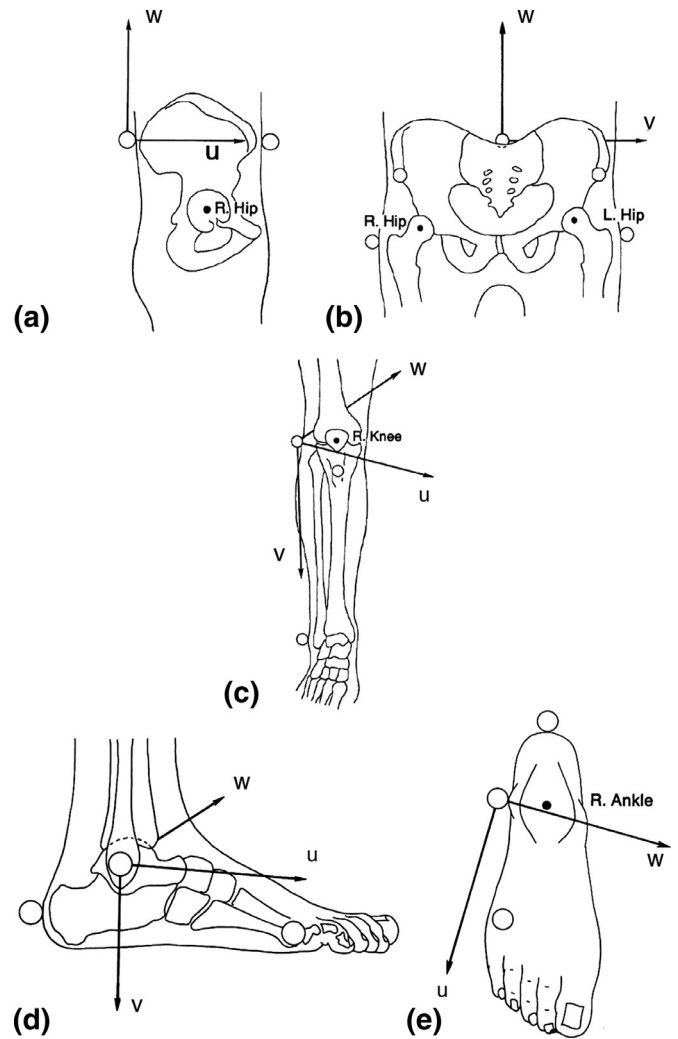

Fig. 2. The limb segment reference frames as defined in Vaughan I [14]. (a) Pelvis in sagittal view. (b) Pelvis in frontal view. (c) Right knee in frontal view. (d) Right foot in sagittal view. (e) Right foot in transverse view.

Fig. 2. The regression equations by Vaughan I was defined as:

$$
\begin{aligned}
p_{\text{Hip}} = p_{\text{sacrum}} &+ 0.598(\text{ASIS breadth})\mathbf{u}_{\text{pelvis}} \\
&\pm 0.344(\text{ASIS breadth})\mathbf{v}_{\text{pelvis}} \\
&- 0.290(\text{ASIS breadth})\mathbf{w}_{\text{pelvis}}
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
p_{\text{Knee}} = p_{\text{Femoral epicondyle}} &+ 0.423(\text{Knee diameter})\mathbf{u}_{\text{calf}} \\
&- 0.198(\text{Knee diameter})\mathbf{v}_{\text{calf}} \\
&+ 0.406(\text{Knee diameter})\mathbf{w}_{\text{calf}}
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
p_{\text{Ankle}} = p_{\text{Lateral malleolus}} &- 0.008(\text{Foot length})\mathbf{u}_{\text{foot}} \\
&+ 0.393(\text{Malleolus height})\mathbf{v}_{\text{foot}} \\
&+ 0.706(\text{Malleolus width})\mathbf{w}_{\text{foot}}
\end{aligned} \tag{3}
$$

2.3. Regression equations by Vaughan II

Like the regression equations in the CGM, the regression equations by Vaughan II were based on Helen Hayes Hospital marker setup, but the HJC equations remained unchanged from Vaughan I. The knee and ankle **uvw**-reference frames were defined in accordance to Vaughan II as illustrated in Fig. 3 and the equations were defined as:

$$
\begin{aligned}
p_{\text{Knee}} = p_{\text{Femoral epicondyle}} &+ 0.000(\text{Knee diameter})\mathbf{u}_{\text{calf}} \\
&+ 0.000(\text{Knee diameter})\mathbf{v}_{\text{calf}} \\
&+ 0.500(\text{Knee diameter})\mathbf{w}_{\text{calf}}
\end{aligned} \tag{4}
$$